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MESH NETWORKING IN THE TACTICAL ENVIRONMENT USING WHITE SPACE TECHNOLOGY

by

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The transition of the military from wars within two known and established theaters to a focus on a dynamic and hastily occupied combat environment necessitates the need for a similarly dynamic and adaptable communications backbone. Traditionally, Army units have relied on either FM communications over short distances or expensive radios to communicate over long distances. FM communications often require retransmission to extend their reach while expensive radio systems often rely on other resources such as satellites. The analog-to-digital television conversion saw the birth of white space spectral technology, which dynamically allocates unutilized spectral space within the television broadcast range to transmit data. This research explores the use of white space spectral technology in the creation of a dynamically established communications infrastructure for the purpose of repeating communications originating from numerous existing platforms in the tactical environment. A comparative analysis was conducted between an implementation of this technology, the Carlson Rural Connect, and similar solutions, specifically, a variant of the Harris 117G, currently available within the military in order to explore the merit of this technology for use as a communications relay in the tactical environment. The results obtained in these experiments demonstrate the potential use of white space technology as a repeater in the tactical environment. Though this potential exists, this technology requires time, a dedicated development effort, and additional testing and experimentation before it is refined enough for use in military operations.

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MESH NETWORKING IN THE TACTICAL ENVIRONMENT USING WHITE SPACE TECHNOLOGY

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ABSTRACT

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List of Acronyms and Abbreviations

ANW2 Adaptive Networking Wideband Waveform

ARP Address Resolution Protocol

C2 Command and Control

COMSEC Communications Security Encryption Keys

dBi decibel isotropic

DHCP Dynamic Host Configuration Protocol

DOD Department of Defense

FCC Federal Communications Commission

GHz gigahertz

HF high frequency

ICMP Internet Control Message Protocol

JIFX Joint Interagency Field Experimentation

JVAB Joint Vulnerability Assessment Branch

Kbp/s Kilobytes per second

kHz kilohertz

MHz megahertz

NPS Naval Postgraduate School

NSA National Security Agency

NTIA National Telecommunications Information Administration

SATCOM Satellite Communications

SINCGARS Single Channel Ground and Airborne Radio System

TCP Transmission Control Protocol

UDP User Datagram Protocol

UHF Ultra High Frequency

USG United States Government

VHF very high frequency

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CHAPTER 1:
Introduction

Over the course of the nation's last two wars, fought in a counter-insurgency environment, units operating at the tactical level have generally relied on the existence of an established communications infrastructure built up over ten years of operations. As the nation shifts toward a focus on full-spectrum operations in an unknown and rapidly occupied theater, units asked to establish a foothold in this theater will undertake the task of executing operations of a dynamic nature in an unknown communications environment.

The systems developed to leverage the combat enablers, which give these units an advantage on the battlefield, had the luxury of this established communications network when utilized during the nation's last two wars. In the future, this luxury may not be present however, tactical units must still be afforded the means to bring these enablers to bear in combat. These enablers include resource intensive processes such as streaming live feeds from intelligence assets, dissemination of detailed imagery, or transmission of intelligence data.

1.1 Problem Statement

The hasty establishment of a communications infrastructure for units to distribute information on the ground is vital to the employment of enablers and new systems developed to rely on a robust communications infrastructure. The success of operations executed against the near peer enemies American forces prepare to encounter in the future is, to some degree, dependent on these systems. Communications over the horizon and past line-of-sight are necessary to provide capabilities to units on the frontlines of an engagement.

In this thesis, current means to provide inter-theater connectivity will be evaluated and new technology, namely white space technology systems, will be explored in order to attempt to find the system that is most capable of providing persistent, reliable, adaptable, and long reaching connectivity to units at the battalion size and smaller; element sizes vital in operations designed to gain access to terrain in an austere, fluid, and dynamic environment. Systems will be evaluated in terms of several key performance factors including: through-

put at various distances, maximum distance for viable communications links, ability to be used in the tactical environment in terms of usability metrics such as power use, mobility, and ease of use, and key features such as the ability to encapsulate traffic, avoid detection and avoid active jamming. Ultimately, the value of these systems to the tactical units utilizing them and the cost to the organizations providing these systems to tactical units will be evaluated.

1.2 Research Description

The goal of this research is to explore a means through which a network can be established in the tactical environment that allows for adaptable communication over long distances. White space spectral technology, utilizing a frequency range well-suited to long-range communication over variable terrain and spectrum sensing/reacting properties, will be explored as a means to fill this requirement. Experimentation will be conducted which will compare tactical radios currently in the military's inventory using native capabilities against similar radios using white space spectral technology devices for the provision of a communications backbone. This experimentation will seek to simulate the tactical environments that these radios might be asked to operate in during deployment.

Several research questions guide this effort. These questions are as follows:

1. Does a mesh network, utilizing a white space technology backbone, provide tactical units advantages in terms of range, agility and flexibility, ease of use and persistence versus existing means of tactical network construction?
2. Does this network provide a more reliable means of voice and data transmission between units co-located in the tactical environment across various types of terrain than a network provisioned by radios currently in the military inventory?
3. Can this network be expanded in a rapid manner in order to facilitate the movement of tactical units across significant distances?
4. Can this equipment be integrated and used with existing equipment in the military inventory?

1.3 Research Benefits

This study benefits the Department of Defense (DOD) and tactical military units specifically, by exploring the concept of an adaptable, expandable, hastily established, and cost effective network in the tactical environment as a means of increasing the ability of tactical forces to maneuver on the battlefield without loss on critical Command and Control (C2) links, thereby allowing the tactical commander to maintain the initiative and leverage tactical advantages without increasing the risk that distributed forces may become isolated from critical communications infrastructures. This network provides a means to utilize existing and readily available equipment over a backbone designed to adapt to varying spectral environments. This study will provide the background to ensure that tactical units have a means to ensure intra-theater communications, which is vital to mission success.

1.4 Organization

Chapter 2 provides background information on the possible available solutions capable of repeating voice and data communications in the tactical environment. Solutions existing within the current military inventory, in the early stages of fielding, and in the civilian sector will be analyzed and evaluated. The history of white space spectral technology will also be discussed along with its current development in the civilian sector.

Chapter 3 provides details on the experimentation model, the process by which the experiment was established and the metrics evaluated and measured. The specific equipment utilized and the various configurations of tested equipment will all be discussed.

Chapter 4 includes the findings of the experimentation. Measurements taken and analysis will be included.

Chapter 5 includes the conclusions of this research and recommendations for future work.

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CHAPTER 2: Background

Before the wars in Iraq and Afghanistan, the majority of communications at the tactical level consisted of voice transmissions. The prolonged wars allowed for the build-up of a communications infrastructure upon which a significant amount of data could be transmitted between tactical units and pertinent/requisite receivers. Rather than communicating requests for indirect fires or casualty evacuations solely by voice, units operating at the tactical level were now able to utilize data transmissions to request enablers. As the military shifts away from these locations, the tools developed during the last ten years at war remain vital. The provisioning of connectivity to forward units is essential in order to ensure that these tools are useful and that effective communications can take place in theater.

A possible means of provisioning connectivity to units in the tactical environment is the utilization of repeaters. A network of repeaters can be utilized to expand a communications infrastructure dynamically allowing the emplacement of additional nodes on an as needed basis. Additionally, a repeater network typically requires minimal extraneous encapsulation or processing overhead. The limited requirement for additional processing can equate to a decrease in logistical demands. On the battlefield, this may equate to a device with a small footprint in terms of power draw, weight and size. Furthermore, since packets require limited additional processing, there is little need to de-encapsulate the packets, thus encryption can be preserved both in terms of vital equipment on forward deployed devices and unencrypted data moving through a device.

2.1 Current Relay Practices

2.1.1 Provisioning of Satellite Communications

Satellite communications are one possible means to ensure that units located on any portion of a battlefield, located anywhere in the world, are provided connectivity. Satellite Communications (SATCOM) reach back is utilized to provision data connections to units at the strategic and operational level. Extending this connectivity to the tactical level appears to be the next logical step. Though capable of providing communications across long dis-

tances, the demands on SATCOM are extremely high and bandwidth via this medium is a limited resource. Tools utilized at the operational and strategic level can be very bandwidth intensive and may have no other means of communicating save SATCOM.

The Predator platform is an instance of this demand. Predator drones require a great deal of bandwidth as they are controlled via a long reach back to a group of pilots, and the data they collect is large in size and required instantly at many locations. There are no terrestrial based solutions to the provision of this kind of service, and the demands of platforms like this one tax the military satellite fleet beyond its capabilities. In fact, in 2010, the Defense Business Board estimated that the DOD spent 640 million dollars on commercial satellite services to supplement the military's bandwidth capabilities [1]. The board's projection at that time was that the DOD would continue to rely on commercial services to supplement the military's capability in order to fill bandwidth requirements.

Given the strains placed on this platform, there is little promise that it will serve as a solution to the problem of provisioning service to units at the tactical level. There are many platforms available to tactical units upon which they are able to reach back to a satellite source however, the limits of the resource do not necessitate this allocation. Furthermore, units at the tactical level do not often have to reach out of theater for requisite resources. These resources, such as indirect fires platforms, next echelon headquarters, casualty evacuation, and intelligence relays are often co-located with them in theater. These enablers must be located in the general vicinity of a battle in order to be useful. According to Army Field Manual 3-0, the defined footprint of a doctrinal battle, and thus the tactical environment, does not necessitate the need for communications outside of a small geographical area [2]. In the majority of cases, the requirement to communicate within an area of this size does not necessitate the provision of SATCOM resources, saving them for use by higher echelons. In this case, communications for tactical operations can be provisioned by a terrestrial based solution with over-the-horizon/long-range abilities.

2.1.2 Current Ground-Based Radio Solutions

Current tactical communications rely on ground-based radio systems in order to deliver information in theater. These systems utilize various frequency ranges, depending on provisioned equipment, to transmit voice and data traffic.

The Army field manual that covers tactical radio operations extensively covers the Single Channel Ground and Airborne Radio System (SINCGARS) radio [3]. Arguably the most utilized radio in the Army's inventory, the SINCGARS radio operates with a 25 kilohertz (kHz) separation from 30-88 megahertz (MHz). This radio is equipped with two native power output settings that give it a theoretical range of 200 meters for the low setting and 10 km for the high setting. The currently employed versions of the SINCGARS radio are also capable of receiving approved and officially distributed encryption keys and encrypting traffic for secure communications in multiple environments.

The use of the very high frequency (VHF) waveform in the SINCGARS radio makes this family of radios more difficult to use over unknown terrain than high frequency (HF) radios. The radio has difficulty transmitting over mountainous or hilly terrain since the terrain blocks transmissions and, unlike HF waves, the VHF waves do not reflect off of the ionosphere. These waves are often affected by electronic emissions in built-up areas as well. VHF waves are typically utilized for line of sight communications due to these properties. This, in turn, produces significant limitations for the SINCGARS radios. However, this radio remains a very widely utilized platform due to its distribution throughout the military and its relative low cost.

In order to extend the communications range of these devices, an intermediate retransmission of radio communications is often utilized. Though this practice can extend the communications range of this platform, it comes with a cost. The retransmission of a VHF signal in the tactical environment requires a great deal of planning and manpower. Site selection is critical given the limitations of signal propagation, so reconnaissance is usually required to some extent before a site can be established. Retransmission with a SINCGARS radio is also equipment intensive, requiring at least two SINCGARS radios, a large antenna mast, amplifiers and power. After all this equipment is emplaced, it must be manned and secured in order to ensure it is protected and continues functioning properly. Site establishment also requires specially trained and knowledgeable personnel who are able to troubleshoot and setup the requisite equipment.

An alternative or complement to the SINCGARS radio in the tactical environment is the HF radio. The most commonly deployed military radio capable of broadcasting in the HF range is the AN/PRC-150. This radio is capable of operating from 1.6 to 29.9999 MHz,

using skywave propagation, and from 20 to 59.9999 MHz using FM with a maximum output of 10 watts. This frequency range allows for a signal to propagate a great distance and bounce off of the ionosphere to extend communications far beyond line of site, but the extended range of the high frequency wave form does not come without trade-offs. High frequency communications are very susceptible to environmental conditions; changes in sunspot activity and weather can impact communications. Operating devices that send and receive HF communications also require an increased level of technical knowledge. Army Field Manual 6-02.53, which specifies field expedient means of improving signal quality on both the sender and receiver end of communications [3], provides an example of the complexities of operating this piece of equipment. This field manual is dedicated to improving a single aspect of high frequency radio operations.

The adaptations and work-around developed for these platforms make them adequate, in most cases, for voice communications, however data presents a major hurdle. In the case of both of these systems, the provisioned data rate is dependent on signal quality between sender and receiver. There may be solutions to achieve a higher quality of signal but, as discussed previously, they are resource intensive. This is compounded by the fact that these systems are hindered by antiquated technology. In the case of the SINCGARS, the Army Field Manual lists the maximum data rate at 16 kbps and the AN/PRC-150 has a data rate listed at 9.6 kbps. It is apparent that, even under ideal conditions, the data rate for these two platforms is inadequate by practical standards based on the current demands of video and image transmission alone.

2.2 Modern DOD Utilized Solutions

Several solutions to this communication problem are in development or in the early stages of fielding throughout the military. The systems discussed within this review are not all encompassing of the many systems being developed to solve communications issues. The systems discussed in this section, namely the Harris AN/PRC-117G and Persistent Systems Wave Relay suite, are example of systems utilized by some portion of the military to communicate. Many other communications platforms exist throughout the military that could serve as an extension of communications capability. However, the use of these platforms is not widespread and accepted as a common practice. There are several possible reasons why this might be the case, including widespread availability of the platform, cost of equipment,

or on-going testing prior to a commitment to purchase throughout the DOD.

2.2.1 Harris AN/PRC-117G

The Harris Corporation Falcon III AN/PRC-117G is a radio that has already seen deployment throughout the military. The AN/PRC-117G is a software-defined radio designed for tactical use that is capable of operating from 30 MHz to 2 gigahertz (GHz) with a power output of 10 watts VHF and 20 watts Ultra High Frequency (UHF). This radio is National Security Agency (NSA) Type-1 Certified to transmit encrypted information and is capable of transmitting numerous waveforms including: SINCGARS, Havequick II, VHF/UHF AM and FM, High Performance Waveform, Military Standard SATCOM, and Adaptive Networking Wideband Waveform (ANW2).

The AN/PRC-117G is a unique solution to providing long-range tactical communications because of the numerous supported waveforms and the radio's ability to be integrated into a tactically deployed network. ANW2 Revision C facilitates networking by utilizing the AN/PRC-117G. This waveform is an ad-hoc, self-forming, self-healing networking waveform capable of adding and dropping nodes from the network using beaconing signals sent every 135 milliseconds by each node. It also supports channels at 1.2 MHz and 5 MHz bandwidth sizes. ANW2 Revision C also utilizes Dynamic Channel Allocation to improve system data capacity to up to 10 Mbps in 30 node networks [4]. ANW2 Revision C uses Time Division Multiplexing and Dynamic Channel Allocation as part of the Harris Corporations proprietary means of allocating channels within the utilized spectrum range divided up through a defined time range [5].

The AN/PRC-117G has been fielded for several years but, it has not yet become the most widely deployed radio system throughout the military for several reasons. This is partly because in most deployments, it is part of a suite of radios that facilitate communications architecture, reducing the number of deployed AN/PRC-117G radios. These suites may incorporate radios that broadcast at different frequencies for longer reach, such as HF, or radios that do not require the network configuration time and overhead of the AN/PRC-117G. The AN/PRC-117G also lacks the ability to adapt to the spectral environment that it is being used in and can experience significant degradation of service due to interference. Research has been conducted into providing a spectrum adapting capability for this

radio [6]; however, this feature is currently not in widely available or fully developed. The AN/PRC-117G is also cost prohibitive. At more than 30,000 dollars per radio, it is very costly to outfit them across an organization in the same manner that the SINCGARS radio, averaging one-third this price, has been deployed. Additionally, Harris AN/PRC-117G radios are classified as Type 1 encryption products by the NSA. This means that the devices themselves are considered very sensitive and contain equipment necessary to preserve important encryption schemes and information. For these reasons, utilizing the AN/PRC-117G as a repeater is not practical. A deployment of this device will inherently demand the necessary manpower to operate and secure it.

2.2.2 Wave Relay Solution

The Wave Relay suite, produced by Persistent Systems, is a mobile ad-hoc networking system that utilizes proprietary routing and network forming algorithms. Devices within this suite are available in multiple configurations, depending on the capabilities desired. This suite is capable of incorporating ten different transmitting devices that can broadcast at a frequency range from 760 MHz to over 5 GHz. This system is capable of transmitting at 37 Mbps UDP and 27 Mbps TCP via a 20 MHz channel [7]. Unique to this device is the proprietary networking architecture, which creates an adaptable mobile ad hoc network that can be rapidly expanded to allow for greater network reach.

When compared to the other devices and technologies discussed, this device is unique in several ways. The proprietary means of establishing a mobile ad hoc network differs from that utilized by Harris and the proprietary ANW2 waveform. Also, the Wave Relay system does not have the ability to analyze and adapt to the frequency environment by adjusting the transmission frequency of the system. The system is capable of broadcasting at several different frequencies, but rather than utilizing software defined radios, this system utilizes platforms that integrate radios capable of broadcasting at different set frequencies into the system, such as the Wave Relay Quad Radio Router [8]. The Quad Radio Router is capable of incorporating four separate radios, each operating at a unique frequency, to communicate within its network. This does increase the frequency use capabilities of the system; however, it differs from the White Space solution in that it is not adaptable, and it differs from the Harris solution in that a maximum of four frequencies are available depending on the hardware configuration of the Quad Radio Router.

Given these limitations, this radio system was not examined during the course of this research.

2.3 White Space Spectral Technology Relay Solution

In the United States, the Federal Communications Commission (FCC) and the National Telecommunications Information Administration (NTIA) handle frequency allocation to various federal and non-federal agencies. Up until 2009, the FCC provisioned frequency range within the VHF and UHF bands to analog television. The majority of the frequency range from 54 MHz to 890 MHz was broken into approximately 6 MHz channels upon which video and audio signals were transported from large base stations to various receivers throughout their broadcast range [9]. For over 50 years, the distribution of channels and use of frequencies within this range remained generally allocated to broadcast television until the analog to digital conversion in 2009.

In 1996, Congress authorized the allocation of additional broadcast channels to the full-power television stations throughout the country in order to begin the transition from analog television to digital broadcasts, a transition driven by advancements in television technology. Due to the adoption of digital television broadcast and reception technology users could receive an increase in quality within a more compact signal where in audio and visual signals could be combined within a 6 or 8 MHz channel, depending on the host country standard. Within the United States and Asia, 6 MHz was adopted as the standard channel size. Most of Europe chose to utilize 8 MHz size channels. The transition was pushed back several times from 1996 to 2009 in order to ensure the transition of the maximum number of users [10]. By June 12, 2009, the FCC declared the transition complete.

This transition freed up a considerable amount of space in terms of usable frequency throughout the range once utilized by analog television. The 700 MHz frequency range is an excellent example of this reclamation. Prior to the analog to digital transition, this 100 MHz range had been dual utilized by medical equipment and wireless microphone type devices. Along with the transition the use of these devices in this frequency range was restricted and the majority of television channels fell beneath this range. The FCC decided to reclaim this band in its entirety and allocate most of it for use by public safety entities. The rest of the band was auctioned off for continued commercial use outside of the realm

of television [11]. However, reclamation of unused space in this manner was not the norm; the majority of the open space is made up of channels fractured throughout the frequency range rather than large blocks of space that can easily be managed and reclaimed.

2.3.1 Utilizing White Space

White space, as it relates to the spectrum, refers to portions of licensed radio spectrum that licensees do not use all of the time or possess in all geographical locations [12]. In the United States, a significant amount of push back emanated from the broadcast industry regarding the use of white space. In 2007, several large technology companies, many of whom joined the Wireless Innovation Alliance, formed the White Spaces Coalition [13]. These organizations began working with the FCC to establish rules for utilizing the white space within the spectrum. In 2009, the National Association of Broadcasters filed a lawsuit that would effectively ban the use of this unused space, claiming these devices interfered with traffic on allocated frequency ranges [14]. This suit was not dropped until May 2012. During that time the FCC established stipulations regarding the use of white space. The FCC decided that devices utilizing unregistered frequency must either utilize geo-location and a database that contains all registered frequencies in use in an area or must be capable of listening in order to de-conflict use of a particular frequency with users already operating on that frequency [15].

All devices within the United States, utilizing unregistered frequency ranges to broadcast and receive information, poll a database that contains all registered channels and their owners. A commonly used database is the Google Spectrum Database [1]. This database consists of a GUI interface and an API for use by developers of white space devices. The GUI allows the user to search for a particular address and determine the state of the registered spectrum at the address searched from different broadcast heights or a fixed/portable position. The database also contains the registered owners of a channel. The API performs a similar function however it is optimized for use by developers in applications that provide functionality to devices seeking to allocate unutilized spectrum space. The devices are able to poll the database, via a connection to a web based database, and determine which channels are available for use. Software within the white space device takes information from the database along with information provided by on-board spectrum sensing tools and

[1] https://www.google.com/get/spectrumdatabase/channel/

determines an optimal channel for communication.

Besides the ability to poll a database, arguably the most critical function of a white space device is the ability to analyze the spectral environment and determine a suitable channel to utilize based on the traffic present. When coupled with a database, this feature can ensure that the radio is free to operate without interfering with registered traffic and without degrading its own performance by competing with concurrent traffic on a channel on which it has chosen to broadcast.

Currently, a common employment of white space technology is the provision of connectivity to rural locations. The system has been deployed in several locations within the United States and abroad. Most notable are efforts to provide connectivity over long distances to population centers in Africa that do not have any means to acquire traditional connectivity solutions. A project in Namibia, sponsored by the MyDigitalBridge Foundation, uniquely attempted to cover an area 62 km x 152 km in size. This area contained are three regional councils and 28 schools, all of whom were provided Internet connectivity by Adaptrum white space devices [16]. The use of white space devices made this deployment the "biggest white space project of its kind in terms of area of coverage" according to the MyDigitalBridge Foundation, Microsoft, and Adaptrum. Due to propagation properties, fewer devices have to be utilized, reducing cost over a Wi-Fi or mobile solution, and the data rate was sufficient to provide a usable connection.

A second notable implementation is the provision of connectivity to the campus of West Virginia University. On July 9, 2013, West Virginia University unveiled a campus wide white space network, touting it as the first of its kind in the United States [17]. This white space network implementation is utilized to provide connectivity to university students and faculty on campus and the surrounding areas. According to the press release detailing the universities deployment, white space technology allows connectivity to be shared with students riding on the university's system of public transit vehicles traveling many kilometers away from the antenna distributing the signal. Due to the frequency characteristics used by this technology, vehicles far outside of Wi-Fi range can be reached so that students are able to stay connected while moving around campus without having to rely on a mobile carrier to provide data coverage.

2.3.2 Advantages of White Space Technology Over Existing Technologies

White space technology is the chosen solution for these problems for many reasons but primarily because the frequency range used provides coverage that is far greater than current Wi-Fi coverage ranges. Operating at 2.4 or 5 GHz Wi-Fi signals are not able to travel very far or penetrate structures well. In 2012, a study was conducted by the British Broadcasting Corporation in an attempt to analyze coverage in an urban area with competing signals and built-up structures [18]. According to this study, even within this restrictive environment significant coverage was experienced out to 1.5 km, a distance not achievable by a traditional Wi-Fi Device.

Though these ranges may seem more reasonable for cellular solution implementation, white space technology has a significant advantage in terms of price while maintaining a wave proliferation advantage. Cellular devices usually operate at a frequency between 700 - 850 MHz or 1700 - 2100 MHz, typically higher than that utilized by a white space device. In many rural areas, the cost of building up a cellular telephone network is simply not reasonable. There is a great deal of equipment that must be emplaced in order to operate a cellular network whereas a white space device can be emplaced for a fraction of the cost and with very little equipment. Each device is capable of functioning as a server or client thereby facilitating the growth of the network.

The final significant advantage provisioned by white space devices, is the ability of these devices to evaluate the spectrum and de-conflict its use. This functionality not only facilitates the efficient use of the spectrum in a built-up area, but it also facilitates the provision of connectivity in a rural area where spectrum usage may not be effectively utilized. In this case, the only way to determine available frequency ranges may be to analyze the traffic in a particular area and make a dynamic allocation for use by a network. Since that functionality is inherent in white space devices, they can handle these situations with little difficulty.

These features lend themselves to solving the problem of provisioning service in the tactical environment. The frequency range utilized by this device and its adaptive capabilities make it ideal for an unknown spectral environment. The waveform is proven to work both in rural

and built-up areas consisting of various terrain and this technology's ability to avoid overcrowded spectral space lends itself to the delivery of usable connectivity. The technology lacks many features that would allow it to serve as a standalone communications platform, but instead this device can be emplaced so that devices in the military inventory can utilize the network created as a backbone for the extension of communications over long distance in a reliable manner. Table 2.1 provides a comparison between white space technology devices and other devices discussed in this chapter.

Table 2.1: Comparison of capabilities between white space and competing technologies

Medium	Frequency Range	Layer	Type 1 Encryption	Power Output	Throughput	Adaptable to Spectral Environment	Current Deployment/ Availability	Cost
SATCOM	1-40 GHz	2/3	Yes	varies	varies - dependent on resource availability	No	Widely Deployed	High
Mil-Spec Radio (HF) AN/PRC-150	1.6 - 60 MHz	3	Yes	10W max	9.6 kbps	No	Widely Deployed	Low
Mil-Spec Radio (FM)	30 - 88 MHz	3	Yes	1 mW, 100mW, 5 W, 50 W with amplifier	16 kbps	No	Most Widely Deployed Platform	Low
AN/PRC-117	30 MHz - 2 GHz	3	Yes	10/20 W 50 W with amplifier	10 Mbps	No	Limited Mil Deployment	High
Wave Relay Suite	760 MHz - 5 GHz	2/3	No	5 W average	41 Mbps UDP 31.1 Mbps TCP	Requires Hardware Exchange	Limited Mil Deployment	High
White Space Spectral Technology	400 MHz - 1 GHz	2	No	100mW 1 W with amplifier	1-16 Mbps	Yes	No Mil Deployment	Low

2.3.3 Equipment Utilized For This Study: Carlson Wireless Technologies Rural Connect TV

There are many companies currently working on devices in this field, however Carlson Wireless, based in Arcata, CA, currently has several products within the white space radio category. The Rural Connect TV is a suite of radio equipment that utilizes white space in the frequency range from 470 to 790 MHz and is capable of providing from 1 to 20 Mbps of data service to an end user. The Rural Connect radio suite is designed to facilitate the establishment of a point to multi-point network topology. The base station node handles the compilation of data necessary to determine a frequency upon which communications can be conducted. This base station contains the software that polls the FCC compliant database listing registered stations in the area and the software that allows the radios to analyze the spectral environment and determine the best channel and modulation to utilize for transmission. The radio uses the information gathered from online databases and the scans of the resident spectral environment to determine a 6 MHz channel that will be utilized by all devices to communicate back and forth.

This device is capable of operating at several different modulations in order to ensure com-

munications between nodes. Modulation selection is dependent on signal strength with higher modulations requiring a stronger signal while providing higher data rates. Table 2.1 depicts the specifics regarding the relationship between signal strength, modulation selection, and data rate:

Figure 2.1: Carlson Wireless modulation use table, from [19]

Downlink TCP/IP	OTA rate in Mb/s	Modulation	Distance in mi	Base Ant Gain in dBi	CPE Ant Gain in dBi	RF Cable loss in dB	Frequency in MHz	ERP in dBm (Client)	Rx Threshold in dBm	Link Margin in dB
2-3	4	BPSK	16	5	9	2.0	574	32	-96	22.9
2-3	4	QPSK 1/2	14	5	9	2.0	685	32	-93	19.6
3-4	6	QPSK 3/4	10.4	5	12	2.0	573	36	-91	24.7
5-6	8	16QAM 1/2	5.2	5	10	2.0	695	34	-86	22.0
7-8	12	16QAM 3/4	3.7	5	12	2.0	590	36	-84	26.4
10-11	16	16 QAM	2.4	5	11	2.0	490	35	-80	28.8

The base and client nodes are capable of transmitting at just under .4 watts on the designated channel and the network created by one base station is capable of accommodating 10 clients. Several configurations of the system are available, however for the purpose of this research, a suite composed of one base station utilizing a Carlson Omni-Directional antenna, depicted in Figure 2.2, was utilized. The omni-directional antenna has a 360 degree beam width and a gain of 6 decibel isotropic (dBi). The client nodes utilized a directional log periodic yagi antenna, depicted in Figure 2.3, with a gain of 8 dBi.

Figure 2.2: Carlson Wireless omni-directional antenna, utilized with base station node

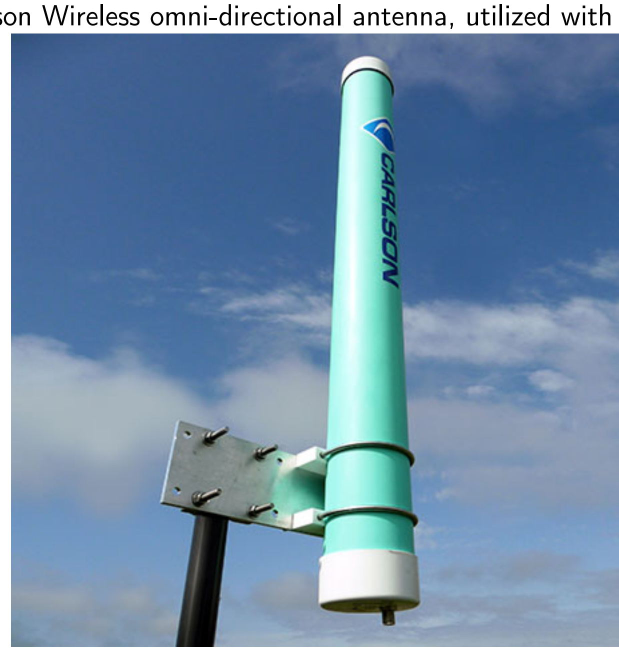

Figure 2.3: Carlson Wireless yagi antenna, utilized at client nodes

For the purposes of this study, the Carlson RuralConnect TV will be utilized to provide a proof on concept of the use of White Space Spectral Technology, deployed as a repeater to provide extended communications in the tactical environment. Various methods for allocating spectral space, de-conflicting the use of this spectral space with adjacent devices, and communicating this channel selection with client devices have been explored [20]. Carlson employs a proprietary means of accomplishing this task which is outside the scope of this thesis; rather, the benefits of this provisioning, use of this waveform, and means of exploiting this technology for tactical use will be demonstrated via this radio.

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CHAPTER 3:
Methodology

Given a platform that promises to provide a solution to tactical, over the horizon, and high bandwidth communications, experimentation and analysis must be executed in order to validate the potential of this solution. In order to determine the viability of white space spectral technology as a means of relaying communications in the tactical environment, it is necessary to examine the radio according to several criteria. Several lines of experimentation are necessary to determine if the radio is able to function in this environment and assess how this functionality compares to currently available military specification radios.

3.1 Experimentation Goals

The essential criteria include several key characteristics that are vital to tactical communications and the execution of the data hungry tasks that have become associated with modern warfare. In this effort, the radio must be evaluated according to its suitability for these tactical operations based on both performance and usability criteria.

Though the suite tested is not specifically designed for the purpose explored by this experimentation, subjective criteria must be evaluated to determine if the potential for development to meet these specific requirements exists. To this end, equipment utilized in this environment must be relatively lightweight and compact in order to be mobile. These modern developments have also increased the space and mobility demands on tactical units and, in many cases, this equipment may need to be carried by a small group or transported in a small military vehicle. The necessity for a large amount of equipment could be a hurdle to the overall usefulness of the system as a whole. It is possible that the base station site might be able to handle an increased amount of equipment as it relies on a reach back to the Internet and would most likely be co-located with additional communications equipment. Client nodes must maintain a small signature, as these are the nodes that would be pushed to the forward lines of the communication infrastructure. Through the various lines of experimentation the size and mobility of the white space suite was evaluated.

Power consumption closely follows the footprint requirement. Power is a very limited

resource in the tactical environment. There are few sources available to power equipment on the front lines of a conflict. The devices drawing power from a storage medium must draw a negligible amount of power in order to ensure that other devices essential to the execution of tactical tasks are also able to draw power. These devices must use power from a battery in an effective manner, meaning that commonly utilized military batteries are able to power a device for a significant amount of time. In many cases, a piece of communications equipment would be required to draw power over a long period of time to facilitate communications. Due to these factors, the power draw of the system must be evaluated at all node types.

Ease of use is also essential to the operation of a communications platform. Specially trained personnel may not be available in the tactical environment and the provision of a device that handles network establishment may reduce the personnel necessary to execute front line operations. This being the case, the speed and ease with which the network can be established, changed and adapted to the environment is essential to the overall evaluation of this suite.

Equipment that meets the above criteria is currently deployed throughout the military and though this criterion is essential to tactical operations, the areas white space technology might improve upon are more performance based in nature. Extensive analysis will be conducted to evaluate the throughput available utilizing the white space suite and the manner that various conditions affect this operation. In order to conduct these tests, several variables will be changed in order to determine the effects on the system as a whole. These variables include the terrain experiments were conducted on, the distance of the client nodes from the base station node, the number of client nodes, and the network topology.

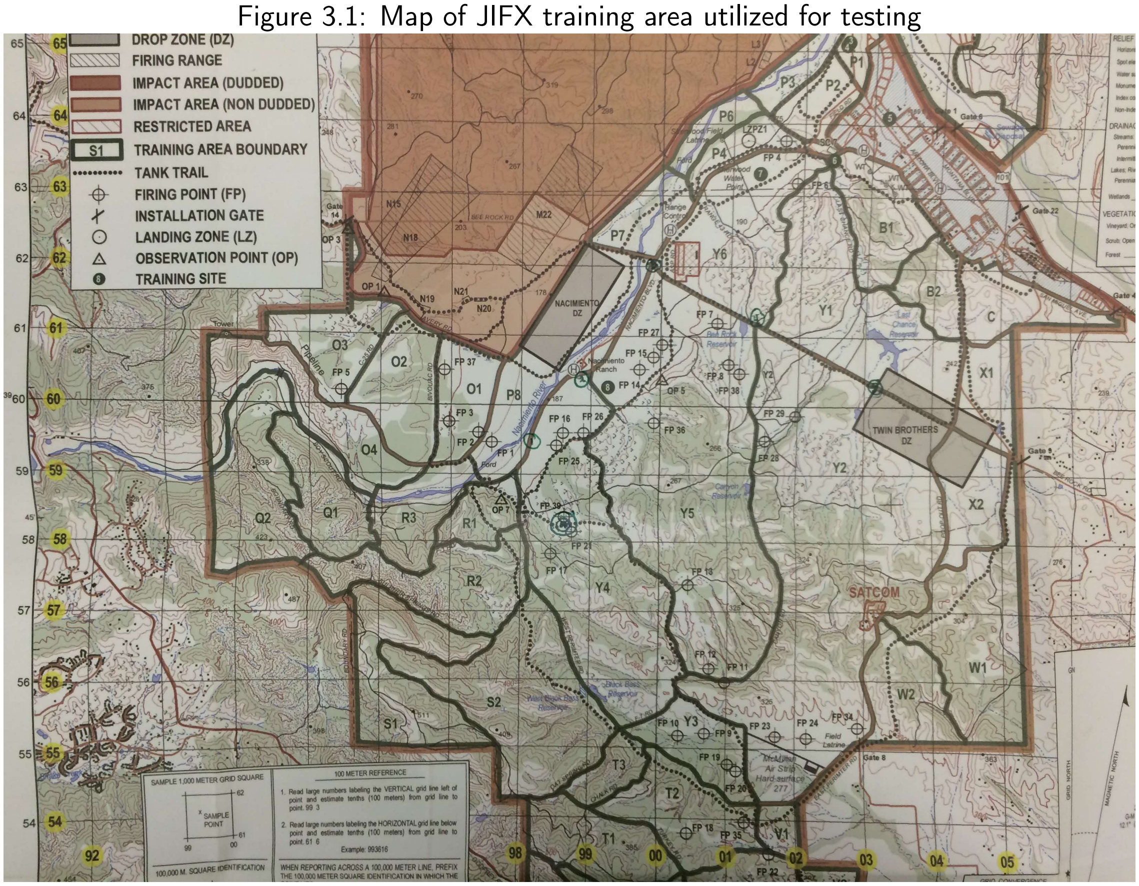
The metrics chosen for evaluation were picked as a means to display the performance of the white space radio suite versus current military specification equipment and to display the potential, given continued development of the technology. These metrics included the throughput experienced on the system, various measurements regarding the signal strength shared between the radios, and the latency that is produced while executing various tasks. Furthermore, several experiments were conducted in order to determine if a task is possible on this suite in order to establish a capability that might be valuable given continued development. The results of these experiments are not captured via measurements but rather

through the success or failure of the task.

3.2 Lines of Experimentation

Given a set of desired metrics, a series of experiments was devised in order to measure the performance of the Carlson Rural Connect based on these pre-determined metrics. The majority of these experiments were conducted on the training grounds at Camp Roberts, California, during Joint Interagency Field Experimentation (JIFX) 15-04 hosted by the Naval Postgraduate School. Camp Roberts and the JIFX provided an environment, both on the ground and in the spectrum, where outside variables could be controlled and mitigated in order to examine the performance of the radio systems utilized throughout these various experiments. The sites utilized for testing are depicted in Figure 3.1.

Figure 3.1: Map of JIFX training area utilized for testing



The Harris RF7800M-MP radio was chosen as the military specification platform utilized

for comparison to the Carlson Rural Connect suite. This radio mirrors the Harris 117G in all features except that it does not support the ability to store Communications Security Encryption Keys (COMSEC). Since COMSEC was not utilized throughout the course of the execution of this experimentation, this radio provided a means through which the white space suite could be compared to a radio recently fielded throughout the military, representing modern technology as discussed earlier.

The first series of experiments were conducted to establish a baseline for the performance of the two radio systems. These tests were all conducted over a short range in a very controlled environment. Data was not gathered during these tests for the purposes of comparing the two suites. Rather, data was gathered as a means to hypothesize on expected results during the larger field tests. These tests also provided an opportunity to utilize each radio suite and determine a set of "best practices" for use during testing. These best practices were utilized to develop troubleshooting procedures and to ensure that each set of radios was operating optimally during the tests utilized for comparison.

The primary series of experiments consisted of two sets of tests designed to analyze the relationship between range and throughput in the white space radio, given tactical conditions. Iperf [2] was the tool chosen to evaluate the throughput available via each radio. Iperf, a commonly utilized network-testing tool, was configured to create a uni-directional TCP stream from a server, established at the base station of each radio suite, to a client, established at the client nodes of each radio suite. Testing was conducted after a connection was established between the base station and the client radio node as reported by the user interface equipped on the radio device. The Harris 7800MP does not utilize a base station to client configuration, in this case, one radio was designated as the base station and co-located at the Carlson Rural Connect base station site.

The first set of experiments was conducted as a side-by-side comparison of the Carlson Rural Connect and the Harris 7800 MP. Both radios were operated in as similar configurations where possible. The Harris radio obviously does not have the ability to change frequency automatically so a frequency close to that being operated on by Carlson Radio was chosen, 500 MHz in this case. All other variables were kept constant for each iteration of this

[2] https://iperf.fr

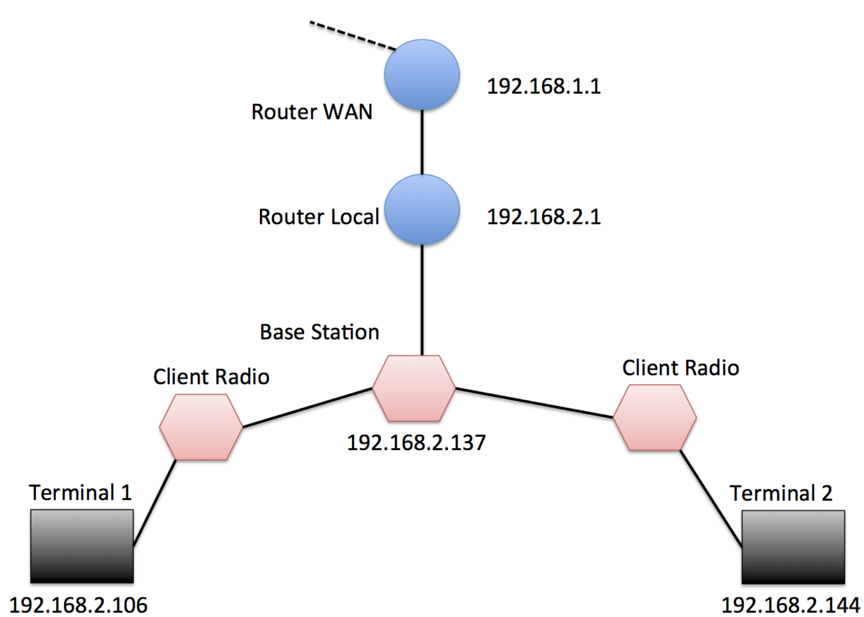
executed line of experimentation; base stations were co-located, as were client nodes.

Execution of the previous line of experimentation revealed that the Rural Connect had the ability to connect with client nodes at a distance that exceeded that of the Harris 7800MP. Due to this finding, a second series of experiments were executed in order to determine the results on throughput experienced via the Rural Connect when distance was increased incrementally. The experiment maintained the configuration utilized in the previous line of experimentation; the sole difference in this case was that the 7800MP was not tested at each distance. The only external variable altered was the distance that the client node was separated from the base station. All other testing parameters remained the same including Iperf settings, power supply, and antenna height and type. One internal factor that was altered both by the user and by the system itself was the modulation that the radio operated at. As previously discussed, the radio is capable of operating at multiple modulation settings. Carlson provides documentation that instructs the user on how to select modulation settings [21]; however, for the majority of the executed tests, the base station settings were configured so that the base station automated the modulation selection process. For the tests executed at the edge of the systems range, manually selecting the lowest modulation rate, in order to produce a reliable connection, proved to be necessary.

The presence of the Joint Vulnerability Assessment Branch (JVAB), a vulnerability probe team, at the JIFX event presented the opportunity to execute experimentation on the jamming resistance properties of the Carlson Wireless Rural Connect TV. The system was not designed for military grade jamming resistance however; the inherent properties of a White Space device imply that some jamming resistance is present in the suite. As detailed previously, White Space devices must sense the spectral environment to determine a suitable channel upon which communications can be carried. The presence of jamming would make a channel unsuitable and necessitate the reallocation of a channel for continued communications. In order to execute this line of experimentation, the JVAB team executed passive scanning in order to determine the operating frequency in use and subsequently, attempted to utilize a software-defined radio to congest the channel utilized by the Rural Connect TV. This line of experimentation produced several pieces of objective data such as whether or not the system was susceptible to passive scanning, its ability to be jammed, its response time to jamming, and its resistance to active jamming efforts.

The third planned line of experimentation sought to demonstrate the operation of the radio over multiple hops. A multi- hop capability is not present in the Rural Connect TV, instead the device is designed for utilization in forwarding traffic to a single distant client node from the Internet reach back at the base station. This line of experimentation sought to work around this limitation by establishing a network utilizing the Rural Connect TV that was composed of two clients connected to a single base station, as presented in Figure 3.2. In this figure the base station is assigned an IP address, 192.168.2.1, from the local router attached to a WAN Router from which Internet reach back is being attained. At one client node, Terminal 1, an Iperf server was established and the adjacent client was attached to the other client node, Terminal 2. This configuration, though not truly a multi-hop configuration, was intended to force traffic generated by Iperf to traverse two transmissions across the Rural Connect network in order to arrive at the server. The traffic would have to travel from one client radio, across the base station node and forward on to the other client radio so that throughput data and the effects of multiple hops on this metric could be observed. Both Terminal 1 and Terminal 2, share a wired connection with their respective client radios.

Figure 3.2: Conceptual sketch of simulated multi-hop network



Following the results of the previous line of experimentation, a subsequent experiment was devised to explore the routing scheme and the division of bandwidth utilized by the Rural Connect suite. In order to explore these characteristics, an analysis between the throughput of the system from the base station node to a single client was compared with the throughput experienced when multiple nodes were transmitted to simultaneously. Data was gathered by comparing the throughput of a network consisting of a base station with a co-located Iperf server and a client with a co-located Iperf client to the throughput of a network consisting of a similar setup, except for the addition of an additional Rural Connect client and Iperf client. This data was then analyzed to determine if there was a significant or detectable difference in throughput when an additional client was added to the network. The purpose of this experiment was to gain an understanding of the bandwidth division that takes place on the system as clients are added, in order to hypothesize on the effects on throughput of a network with numerous nodes.

3.3 Equipment Configuration

All executed experiments shared a similar configuration in order to mitigate the introduction of variables. The physical setup of equipment was composed in a manner that mitigated its footprint and provided maximum mobility.

The Harris 7800MP radios were all operated in a MANPAC configuration with collapsible whip antennas. The MANPAC configuration allows the radio to be carried by a single individual. The ANW2 waveform and configuration software was utilized to create a mobile network between the radios to ensure the utilized frequency was 500 MHz. As discussed previously, ANW2C handles the connection between the radios as well as the network addressing, via DHCP, and routing. Power was provisioned to the radios using BA-5590 rechargeable batteries.

The Rural Connect, having not been developed for military use, allowed for a much more variable configuration. For the purpose of the lines of experimentation described above, a standard configuration was employed. Antennas were all mounted on portable 2-3 meter variable masts. The client radios were also mounted to the masts with the directional yagi antennas. The base station for the system is designed to be rack mounted. In order to utilize it in a tactical environment, a small rack was fashioned to house the radio as depicted in

Figure 3.3. Power was provisioned to the system using several different batteries including BA5590 rechargeable batteries and various sizes of Goal Zero Yeti Batteries equipped with solar recharging panels. The Goal Zero batteries were utilized for tests of longer duration. Configurations for field testing are depicted in Figures 3.4, 3.5, and 3.6.

Figure 3.3: Rural Connect TV base station enclosure

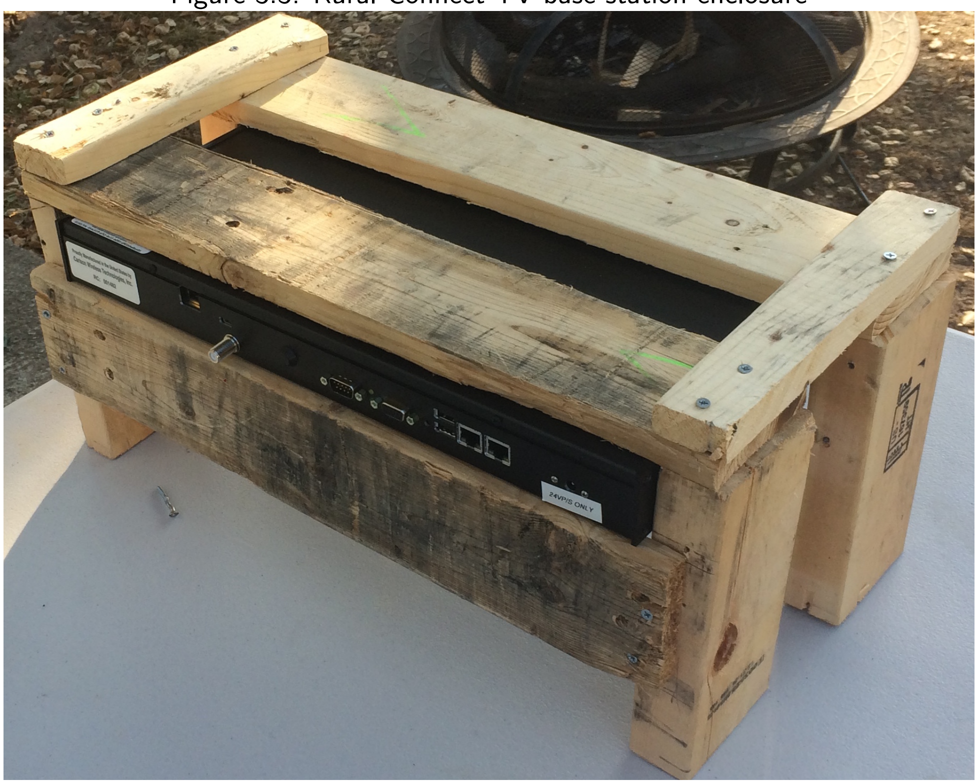


Figure 3.4: JIFX 15-04 testing configuration

Figure 3.5: JIFX 15-04 testing configuration

Figure 3.6: Base station testing site - in the vicinity of OP 7

The Rural Connect TV base station software allows several configurations for the operation of the system. Adjustable parameters include preferred channels, modulation settings, channel analysis and frequency of polling and IP addressing adjustments. As previously discussed, modulation selection was generally handled by the automated processes resident in the base station. In a few cases, the modulation had to be set to its lowest setting in order to ensure a connection either for the purpose of troubleshooting or to maintain a connection at the edge of the suite's reachable range. Images capturing the interface for selecting and observing the radio status and modulation settings on the Rural Connect are depicted in Figures 3.7 and 3.8. The spectrum polling settings were also adjusted in order to facilitate the jamming line of experimentation.

Figure 3.7: Radio status and scanning settings

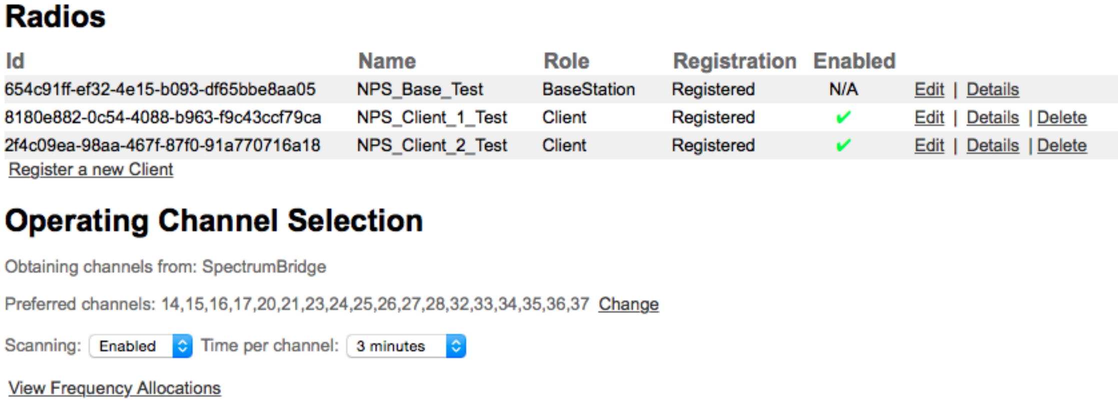
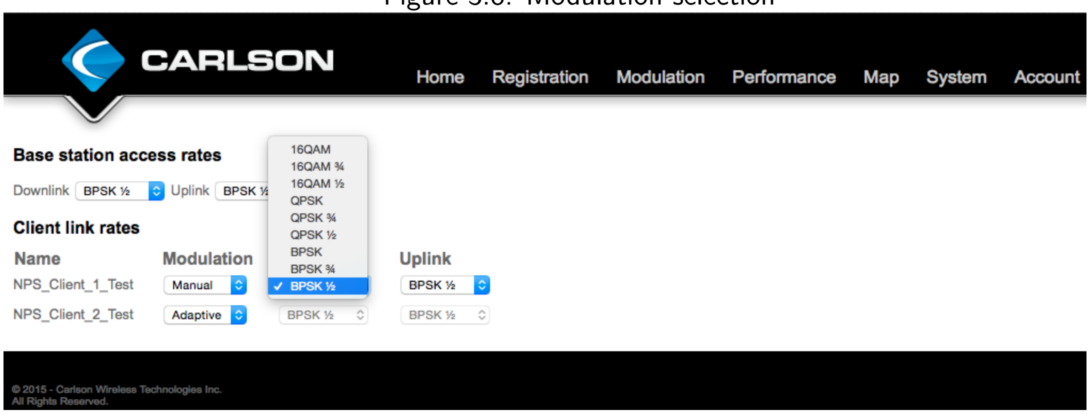


Figure 3.8: Modulation selection



3.4 Multi-hop Simulation

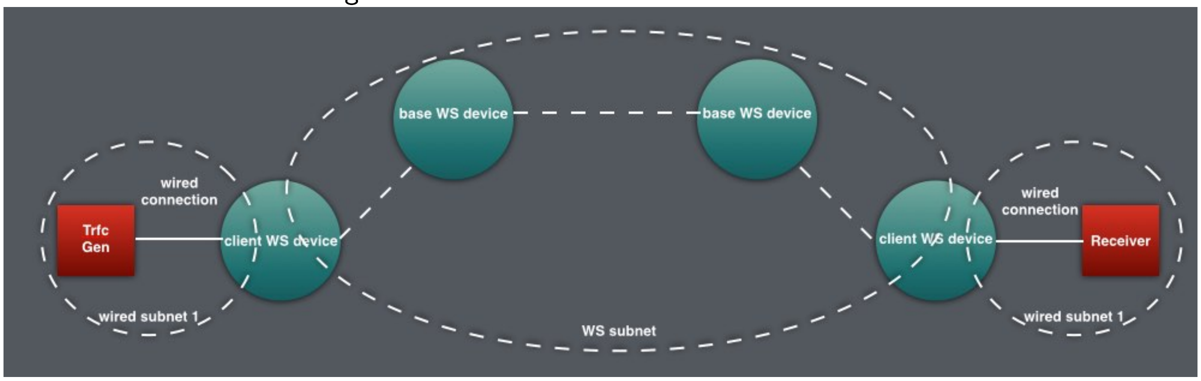
Given the multi-hop limitations of the Rural Connect, simulation was explored as a means to examine the potential multi-hop performance of a white space suite. Current devices lack the ability to support multi-hop networks. However, simulation provides a means to examine performance in terms of data traversing a network which has characteristics that closely mirror the physical characteristics of a White Space network and is equipped with bandwidth division and multi-hop characteristics like those found in Wi-Fi devices. This simulation was not intended to mirror the performance of the Rural Connect due to the existence of proprietary properties that cannot be recreated without knowledge of their operation. Instead of an exact Rural Connect recreation, this simulation is intended to

mirror the general performance of a non-proprietary white space suite by modifying the physical properties of a Wi-Fi model, the free space loss characteristics specifically, while maintaining the properties that allow multi-hop networks to be formed. This new model can then be utilized to provide data that might be utilized to predict the performance of future generations of White Space devices in terms of possible coverage distance, latency increase over multiple hops, and the effects of multiple hops on throughput.

NS-3 was chosen as the simulator to develop these models because it allows for the simulation of the physical characteristics of white space technology and contains models which simulate the requisite properties of network devices with multi-hop capabilities. The data gathered from real world testing, conducted with the Rural Connect suite, was utilized to create and refine the network device module and ensure accurate behavior. Several basic modules within NS-3 presented promise for the implementation of the Rural Connect nodes. The Wi-Fi and WiMax modules were particularly appealing since their modulation schemes are similar to those utilized by White Space suites. The WiMax module was explored initially but it included many features that are not present within a simple White Space device and had the potential to create issues. The Wifi device provided a very basic building block that the White Space device could be built upon so this basic module was extended to create the basics of a multi-hop White Space network within NS-3.

In order to implement a white space device for the purpose of this simulation, several key characteristics were abstracted away because their impact on performance had already been observed or was not important to this scenario. For instance, the frequency sensing and adaptation capabilities of this network are vital to its operation in the real world however, for the purpose of this simulation, the network was modeled as if those decisions had already been made. Node hierarchy was also dealt with via abstraction. White space systems currently available utilize two types of nodes, a base station node and client nodes. Rather than designing nodes with similar propagation properties and different hierarchies, the hierarchies were implemented by enforcing a linear progression of packets through the correct sequence of nodes. All nodes are identical but the nodes with end devices attached, data servers and clients, are placed at the edges of a simple network where all nodes are separated using a mobility model.

Figure 3.9: Simulated network architecture



3.4.1 Simulating Channel Metrics via NS-3 Wifi Module

Critical to the return of realistic results for a multi-hop network via simulation was the accurate simulation of the physical transmission characteristics of the White Space device using the Wifi module. The default Wi-Fi module settings are not configured for the propagation characteristics experienced after a white space device has gone through the process of spectrum analysis, deconfliction, and channel allocation. In order to ensure that these properties were accurately represented by the simulation, a propagation loss model had to be utilized that captured the real world capabilities of the system. In this case the Log Distance Propagation Loss Model was utilized due to its inclusion in the NS-3 wi-fi module and its ability to model exponential path loss. Other models included in the NS-3 wi-fi module, such as the Frii's propagation loss model, are commonly utilized to simulate quadratic path loss across free space [22]. This model uses the following formula to calculate path loss:

$$L = L_0 + 10nlog(d/d_0) \tag{3.1}$$

The parameters utilized to calculate the characteristics of the channel using the Log Distance Propagation Loss module are the reference distance (do) , the reference loss (Lo), and the exponent (n) from Equation 3.1. In order to determine these metrics I utilized the following formula:

$$\begin{aligned} PathLoss =& 20log(d) + 20log(f) \\ &+ 32.44 - G_t - G_r \end{aligned} \tag{3.2}$$

This left only the selection of an operating frequency, a reference distance, and the gain of two antennas in order to calculate the reference loss. A transmission frequency that fell within the range utilized by a White Space system, 500 MHz, was utilized as the frequency for this simulation. A receiver and transmitter gain of 10 dB, a close approximation of the Rural Connect system's antenna specifications, was also utilized to compute the Free Space Loss. These numbers are both realistic and reflect real world experience during testing for this system. A distance of 10 meters was utilized as the reference distance, for the purpose of computing a reference Free Space Loss exponent, resulting in a reference loss of -26.4 dB. In order to calculate the exponent, a second reference distance, 100 m, and loss were calculated and plugged into Equation 1. This allowed the value of n to be found via some simple algebra. The exponent value of 1.998 was utilized as a baseline for the construction of the model. A further analysis of loss was conducted given the data gathered by real world testing and adjustments were made to this exponent in order to reproduce experienced results in a single hop. These factors combined resulted in the production of figures that effectively modeled the physical performance of a White Space suite with the added inclusion of Wifi-like multi-hop capabilities [23].

3.4.2 Testing

Two methods were utilized to test and evaluate the simulated White Space network. The User Datagram Protocol (UDP) Echo Server was utilized primarily to test the routing across the network and also to evaluate latency across the network as the distance between White Space nodes was varied between 500 and 7000 meters. The model was setup to send 5 pings across the network at one-second intervals. Measurements were taken using pcap captures which were also utilized to ensure that all White Space nodes were contributing to the transmission of the packet.

Ping tests facilitated the detection of errors within the simulation. Several issues with the simulation were discovered following the execution of ping testing. The first was the necessity to utilize the Wifi modules Ad Hoc feature. This feature enabled the convergence of the network and allowed some traffic to be forwarded to several nodes. The second issue encountered was the presence of an Address Resolution Protocol (ARP) request issue that seems to affect certain Wifi configurations within NS-3. In order to circumvent this issue, the ARP cache for each node was pre-populated before the simulation was initiated.

After these issues were remedied, ping testing was utilized to confirm that the network was functioning normally and to get a baseline for expected latency.

Throughput testing was conducted utilizing several functions designed to transmit 2 million bytes across the network. Again, pcap captures were utilized to ensure that the data properly traversed the network and that all necessary links performed as expected. Testing was conducted to determine the viable node separation distances and the associated throughput for the system. Throughput testing was utilized to determine the range achievable by a multi-hop system as a whole and the effects of these hops on the latency and data rate of the system. The results of these tests were utilized to hypothesize regarding the real world performance of the white space devices utilized given the case that the construction of a multi-hop network was possible.

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CHAPTER 4:
Findings

Testing conducted at JIFX 15-04 and in a laboratory environment produced a great deal of data for analysis. Though the majority of these findings took the form of performance measurements, a significant amount of data was gathered regarding the subjective performance of the platform.

Subjective data was covered via notes recorded and collected from testing personnel. The testing team at JIFX 15-04 consisted of 3 personnel, all familiar with military radio systems. All personnel provided feedback based on the criteria established in Chapter 3 for later analysis. Findings in this area are particularly focused on the Carlson RuralConnect TV suite since the military specification compliant radio, the Harris 7800MP in this case, is designed for tactical employment. Users evaluated the Carlson Rural Connect's potential for tactical employment and noted any major hindrances encountered.

Performance data was compiled over the course of numerous iterations of testing as detailed in Chapter 3. In the case of the planned multi-hop network tests, inconclusive data was gathered. This resulted in additional research and testing. For all other tests, data was recorded significant to execution. This data includes configuration, significant settings, errors encountered, results and location specifics. The major testing locations utilized for the majority of the experiments executed at JIFX 15-04 can be located in the Table 4.1.

Table 4.1: JIFX 15-04 testing locations and significant radio settings

Test Site	Grid Location (MGRS)	Distance from Base Station	RuralConnect Modulation
Base	10S FE 97723 58573	N/A	N/A
1	10S FE 98130 59528	1.2 KM	QPSK3/4; 16QAM
2	10S FE 99006 60487	2.3 KM	QPSK3/4; 16QAM
3	10S FE 99868 62001	4 KM	QPSK3/4; 16QAM
4	10S GE 01353 61169	4.7 KM	QPSK3/4; 16QAM
5	10S GE 03239 60258	5.8 KM	BPSK1/2
6	10S GE 04350 59762	6.2 KM	N/A

4.1 Employment Potential

The Carlson RuralConnect TV is not specifically designed for mobility or durability under mobile use. However, after several modifications to the manufacturer's installation instructions, a platform for mobile employment was devised. No major modifications were made to the equipment however, some mounting and employment recommendations were not feasible for testing. Specifically, antenna mount height had to be reduced approximately 1-2 meters from the manufacturer's recommendations of between 4 and 6 meters, resulting in a deployment height of approximately 3.5 meters. The size and weight of the antennas did not allow for a practical or safe deployment at the recommended height utilizing mobile antenna masts. This was particularly true of the base station's omni directional antenna. The manufacturer states that mounting the antenna at this height might have noticeable impact on performance and presented Figures 4.1 and 4.2 as a reference for deployments in use given adherence to manufacturers recommendations. The graphs display the change in elevation, represented by the y axis, versus the distance between the base station and client radio, represented by the x axis. These figures depict the potential propagation potential, both in terms of distance and elevation change, of the radio given a refined deployment. In each of these deployments, a steady throughput rate of 2-4 Mbps was achieved, over twice the distance achieved in this experiment.

Figure 4.1: Profile 1 of Carlson Wireless install of Rural Connect system - manufacturer emplacement

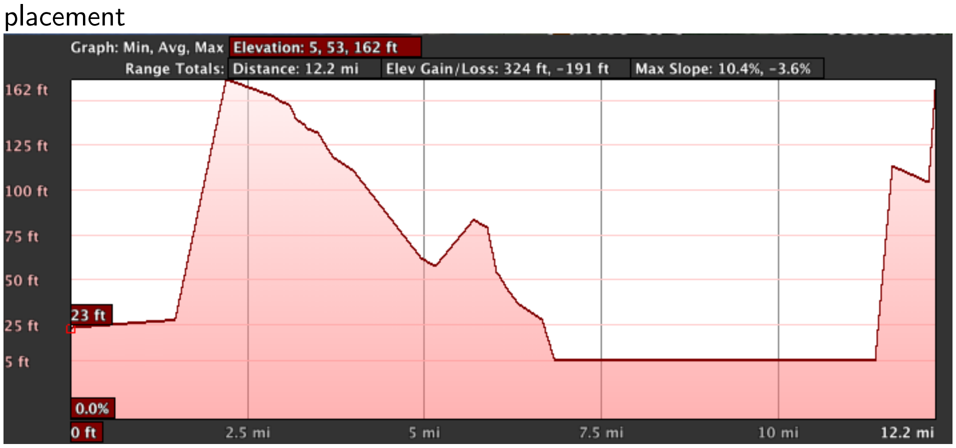
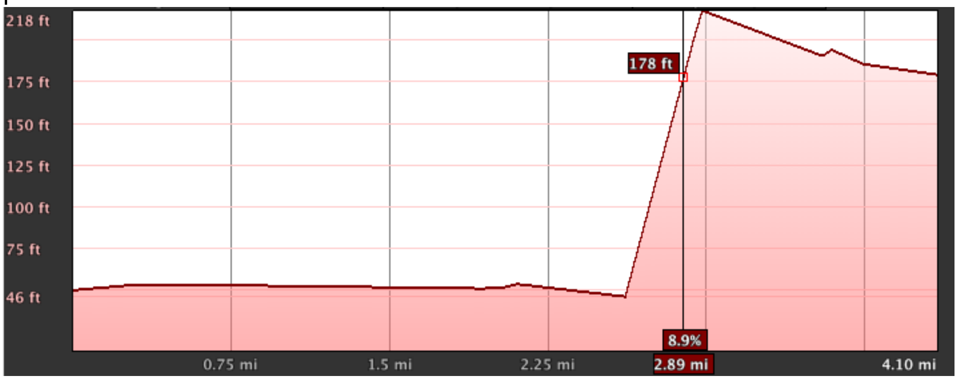


Figure 4.2: Profile 2 of Carlson Wireless install of Rural Connect system - manufacturer emplacement



4.1.1 Capability in the Tactical Environment

As discussed in Chapter 3, the ability for the system to be utilized in the tactical environment was assessed in terms of the mobility and power draw of the system as compared to the Harris 7800MP. The Harris 7800MP, being a version of a device fielded throughout the military, provides an adequate example of a radio that fits ideal deployment criteria.

In terms of power use, the Rural Connect client station operation closely mirrored that of the Harris radio for the purpose of this experiment. The system was able to be powered utilizing several means to include the Goal Zero batteries of various sizes equipped with solar panels and military grade 5590 rechargeable batteries. In the case of the client nodes, no additional power draw was noted as compared to the power draw of the Harris 7800MP.

The base station node analysis did produce a considerable power consumption difference. In the case of the Harris 7800MP, no difference exists between the radios used for client or base station nodes. However, in the case of the Rural Connect base station, the radio itself provides additional functionality that most likely required additional power to be drawn. Additionally, several other pieces of equipment were required to ensure the functionality of the Rural Connect base station. This equipment includes an additional wireless router running in client mode which provides wired Internet connectivity to the base station and allows a laptop to access the GUI and the wireless hotspot, which provisions the Internet connectivity to this router. These additional pieces of equipment draw a noticeable amount of power and increase the overall power requirements of the node. In the case of this

node, a Goal Zero Yeti 400 equipped with solar panels was utilized to power the system continuously for 7 hours. The 5590 battery was found to be insufficient in providing power to the base station node. However the Yeti 400, with a battery capacity of 396 watt-hours, easily powered the system for the duration of the experimentation.

The Harris 7800MP, having been designed with an emphasis on the provision of a mobile configuration for deployment, was again utilized as the standard upon which the Rural Connect was evaluated. Taking into account that the Rural Connect was not designed for a mobile deployment, the client configuration was found to be very mobile. The radios themselves weigh under 10 pounds and when mounted to mobile antenna masts, they were fairly easy to move and deploy.

The requirement for additional equipment at the base station made it much less mobile. As previously discussed, the client and base station nodes for the Harris 7800MP were identical, thus the increased footprint of the Rural Connect base station was significant. Additionally, the increased power requirement necessitated a larger battery which only compounded this increase in size and decrease in mobility. The large physical size of the Rural Connect's omni directional antenna presented an additional challenge. The antenna took time to erect and had to be strategically placed to allow for a safe deployment, utilizing relatively small antenna masts, and effective use of the surrounding terrain.

4.1.2 Ease of Use

After the initial setup of the Carlson Rural Connect TV suite, which included the mounting of equipment, use was fairly simple. The convergence of the network given the correct settings and adequate signal strength, took between 2-3 minutes on average. The process of finding a channel and connecting to clients was automated by the base station.

One major issue encountered involved the strength of the connection to the Internet based database which is utilized to de-conflict channel selection. While located at test site 1 for initial baseline testing during the JIFX event, a usable connection between the Rural Connect base station and client nodes could not be established. At this site, a Verizon cellular hot spot was utilized to provide Internet reach back to the system. After inspecting the connection issue, it was discovered that the available cellular service at this site was not adequate to download database information for use by the base station.

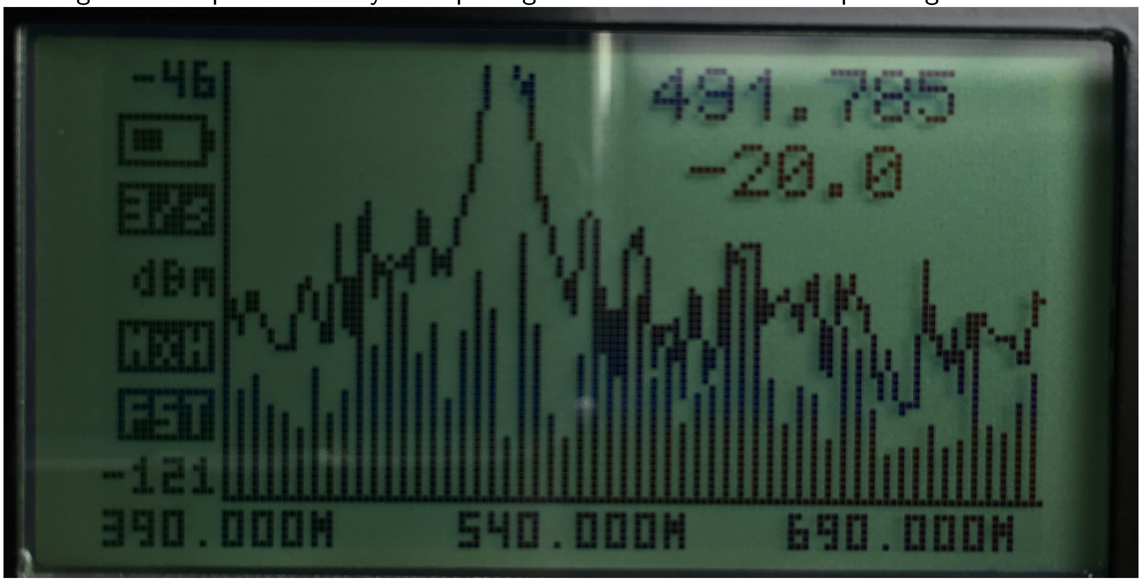
This is the result of a restriction placed on the hardware by the manufacturer in order to adhere to FCC requirements. The radios themselves are not reliant on the database in order to establish a connection. The connection, in terms of addressing and forwarding of information on the Rural Connect, is handled by a weightless link layer protocol as depicted in Figure 4.4. This protocol is non-reliant on Dynamic Host Configuration Protocol (DHCP), but rather utilizes an addressing scheme programmed into the radios. Under fully functioning conditions, the base station designates a channel for communication, the client radios cycle through their frequency range until a base station beacon is found, and once located, they attempt to connect to it. If the base station is associated with a particular client radio it will be allowed to connect. The base station's set of associated client radios was pre-configured into the Rural Connect software by the manufacturer on the system utilized for testing. The lack of connection experienced during experimentation represents an inability for the radios to register, meaning that the database is unavailable for de-confliction between the channel the base station has selected for use and the channels in use within the current location. In this case, the base station's operating channel cannot be selected and thus the client radios are unable to register with the base station.

It is possible to operate the Rural Connect without the ability to access the on-line database. Enabling this capability involves coordinating the location of use with the FCC. For the purpose of this test, and for stateside military use of the radio, this is not practical. Moving the suite would invalidate this coordination and could either result in interference or improper functioning of the radio equipment.

4.1.3 Passive Scanning and Jamming

Passive scans were conducted by a third party, the JVAB team, with the intent of discovering the operating frequency of the Rural Connect Radio. These scans were conducted from the client node, base station, and intermediate locations. In each case the scans were able to detect a significant spike in activity on the channel being utilized by the Rural Connect network. The majority of the scans were conducted at times when no significant data was being sent, by users, across the network. Regardless of data transmissions the operating frequency of the network was able to be accurately detected by passive scanning.

Figure 4.3: Spectrum analyzer depicting Carlson Rural Connect operating at 491 Mhz



Following the discovery of the Rural Connect's operating channel, jamming of the network was attempted via congestion of this operating channel. In this case, a small software defined radio co-located with the base station was utilized to broadcast at the same operating frequency as the Rural Connect network. The attempts at congesting the current operating channel were all effective; during each attempt the GUI depicted the loss of the connection between the base station and the deployed client devices.

The initial iterations were executed with the scanning feature turned off. During these iterations no change was evident after the connection between the base station and client nodes was lost. The system did not appear to allocate or attempt to allocate a new operating frequency and reacquire a connection with the client nodes. After several minutes with no change, this feature was activated. The scanning feature allows the base station to initiate a periodic scan of the spectral environment in an attempt to allocate a new, unutilized operating frequency. The activation of this feature appeared to prompt the system to allocate a new frequency. In this case, the next channel from a predesignated list of channels was utilized by the base station. Once a new channel was allocated by the base station, the client nodes were able to locate and re-register with the base station within 1-2 minutes.

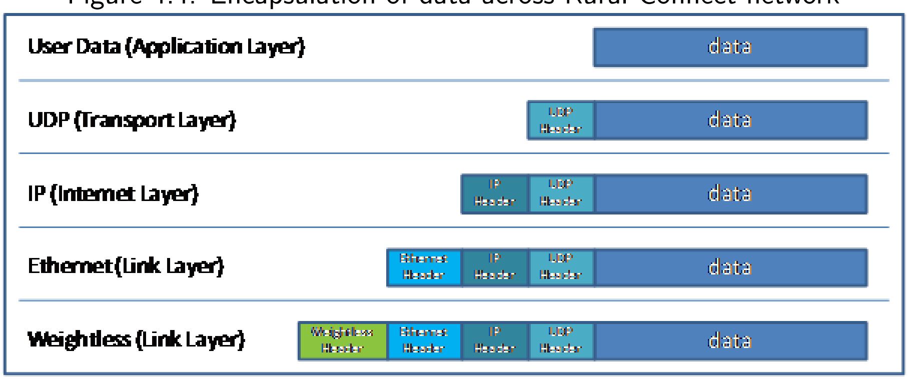
This experiment was repeated several times with the scanning feature enabled. During

each iteration of the test, the results were very similar; the connection between the base and client nodes was lost, a new operating channel was selected by the base station and finally, the client nodes and base station re-established their connection. The process was handled in a very consistent manner by the suite, resulting in no hang-ups or failures to reconnect through each iteration of testing.

4.1.4 Encapsulation of Data over Network

Essential to military tactical communications is the employment of approved encryption for the purpose of preserving the confidentiality of military communications. Devices currently deployed throughout the military utilize approved encryption to transmit data over airwaves. If a white space device is to be deployed as a relay in the tactical environment, then it must facilitate tunneling between clients or rather have the ability to allow data encapsulated within an approved encryption scheme to be transmitted across the network without ever being "in the clear" or decrypted en route.

Figure 4.4: Encapsulation of data across Rural Connect network



The Carlson Rural Connect displays this possibility within a white space device. The means by which data is routed across the Rural Connect network is displayed in Figure 4.4. The Rural Connect network utilizes a weightless link layer protocol that attaches an additional header onto the link layer protocol's header which facilitates addressing within the white space network. The addition of this header is utilized only by Rural Connect hardware for forwarding purposes and provides seamless tunneling of data through the network. The requisite forwarding data, directing data across the Rural Connect network to the correct client, is attached to the packet prepared by the client as it enters the network. Data within

the packet is not altered, and as the data traverses the network it is never in the clear. This weightless link layer provides the necessary functionality to ensure that the Rural Connect device can serve as a relay for end devices providing military grade encryption on the battlefield.

4.2 Comparison to Current Military Specification Meeting Equipment

Modulation settings have a significant and noticeable impact on the performance of the Rural Connect network. For instance, at a distance of 10M, utilization of the BPSK1/2 modulation scheme results in an average throughput of 700 Kilobytes per second (Kbp/s). At this distance, a strong connection is expected and it is likely that a higher modulation will be available for use as either detected by the system or determined utilizing the previously referenced documentation provided by Carlson Wireless. Utilizing the 16QAM modulation scheme at this distance results in an average throughput of 2398 Kbp/s.

For this reason, all comparative tests between the Harris 7800 MP and the Carlson Rural Connect were recorded using the highest modulation scheme available to the nodes on the Rural Connect network. This helps to ensure that an accurate depiction of the peak capability of the system is utilized in the comparative analysis. The data presented in Table 4.2 represents the average throughput resulting from over 60 iterations of testing, utilizing Iperf to perform burst transmissions, between the base station node and a client node for each platform.

Table 4.2: Results of Harris 7800MP and Rural Connect performance comparison

Distance	**Rural Connect**		**Harris 7800MP**	
	Throughput(kb/s)	**Standard Deviation**	**Throughput(kb/s)**	**Standard Deviation**
10	2398.167	617.825	889.083	278.047
800	2158.273	659.014	924.5	210.097
1200	3880.973	2931.867	892	236.759
2300	2938.447	2203.941	8.353	5.018

Figure 4.5: Graph of Harris 7800MP vs Rural Connect performance

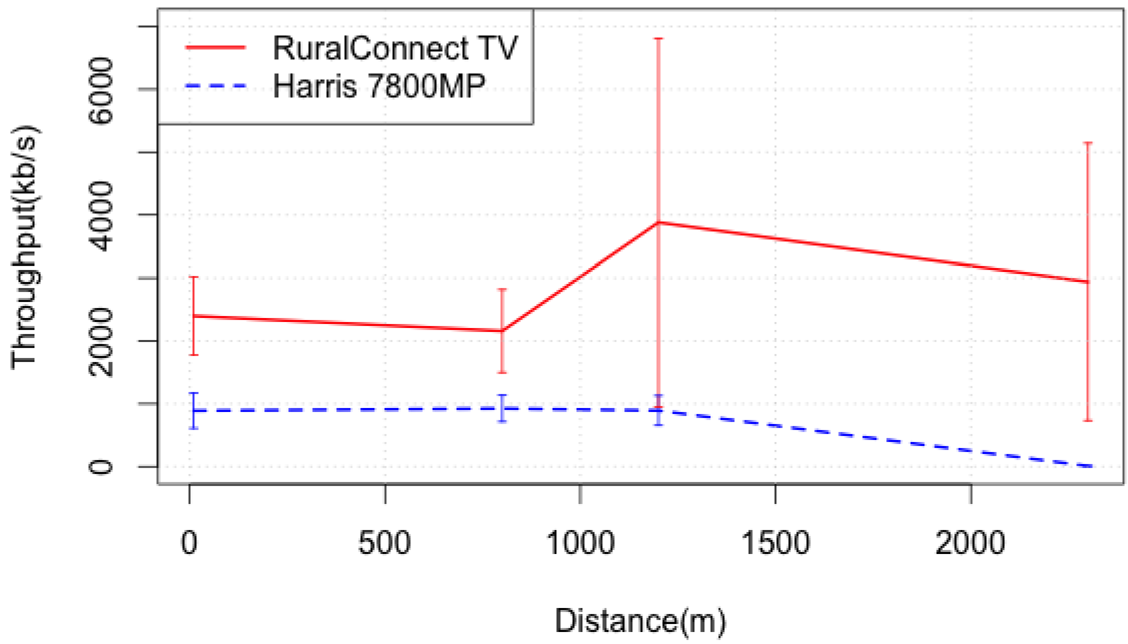


Figure 4.5 depicts the difference in the relationship between throughput and distance experienced utilizing both the Rural Connect and the Harris 7800MP over the course of 4-5 testing iterations at each distance, which were composed of between 10 and 12 distinct measurements each. As depicted in the graph, the throughput at 2300 meters becomes negligible for the Harris 7800MP. A connection between radios was not maintainable past this distance.

One significant variance in results, experienced throughout the course of this line of testing, was the difference in throughput deviation experienced and the difference in this variation between the two radios. The Harris 7800MP maintained a very tight throughput range, as depicted by the error bars in Figure 4.5. The throughput rates experienced throughout the course of all tests executed utilizing this radio were very similar. The Carlson Rural Connect produced much more varied results. There were many testing iterations that produced

results which differed greatly from the average throughput, as reflected by the large margin of error. Despite this large variance, throughput rates experienced at the low end of the Rural Connect's range were still above the average throughput rate experienced utilizing the Harris 7800MP.

The wide range of variance experienced utilizing the Carlson Rural Connect may be the result of the adaptive modulation settings utilized to perform the test. The system is designed to respond to variance in the spectral environment as measured at the base station and client nodes and adjust the modulation utilized for transmission according to these measurements. It is likely that changes in modulation made throughout the course of testing resulted in these varying throughput measurements. In this case, the data rate remains much more stable as there is little adaptation to the means by which the radios attempt to communicate.

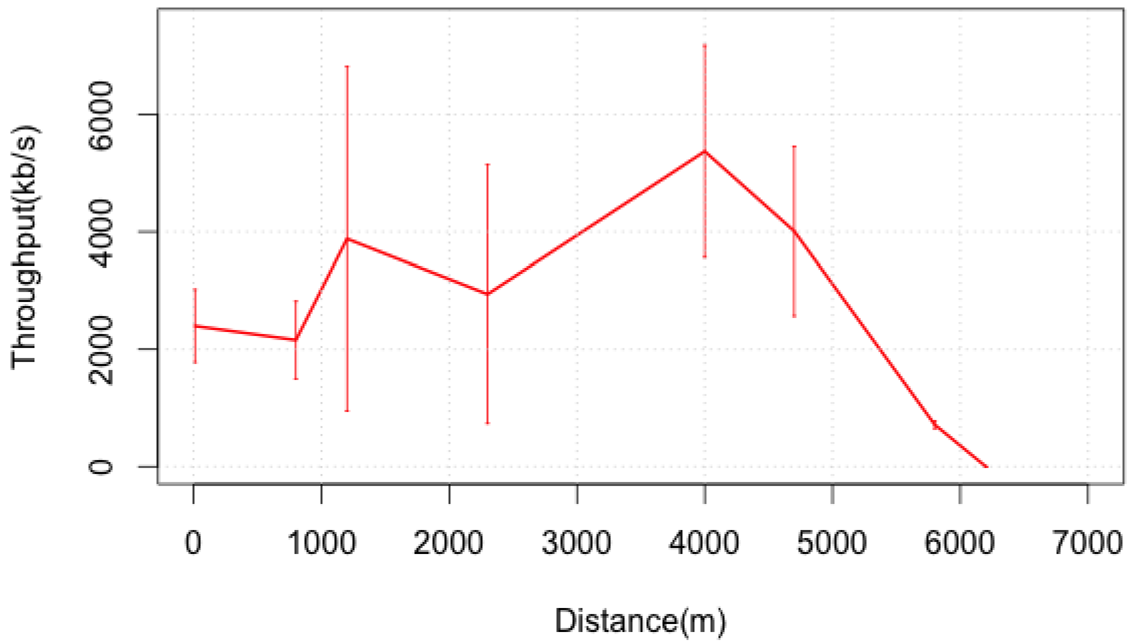
4.3 Tactical Performance

Following the comparison of the Harris 7800MP and the Carlson Rural Connect it was evident that the range of the Rural Connect exceeded that of the Harris 7800MP. In order to fully evaluate the capabilities of the Carlson Rural Connect, additional throughput testing was executed to determine the effects of the terrain and increased distance on the throughput of the suite. Table 4.3 depicts the throughput and standard deviation in measurements gathered from each of the testing locations provided in Chapter 3.

Table 4.3: Results of Carlson Rural Connect throughput versus varying distance

Distance (meters)	**Rural Connect Throughput(kb/s)**	**Standard Deviation**
10	2398.167	617.825
800	2158.273	659.014
1200	3880.973	2931.867
2300	2938.447	2203.94056
4000	5369.705	1804.536
4700	4009.128	1441.032
5800	714.559	62.648
6200	0	0

Figure 4.6: Graph of Carlson Rural Connect performance versus varying distance



As depicted in Figure 4.6, at a distance of 5800 meters, given the terrain and environmental conditions, a viable connection between the client and base station nodes became difficult to maintain. Though the connection was not as strong as experienced at previous locations, the modulation adaptation feature facilitated a connection strong enough to pass a significant amount of data, or approximately 1000 Kbps. Placing the client at a distance of 6200 meters was attempted but a connection was never achieved with the base station at this distance and thus no data was passed between the two nodes.

A notable factor in this test, as experienced in the previous comparison test, was the significant variance in data rate experienced throughout the course of testing. This variance is represented by the large error bars present in Figure 4.6. As in the previous line of testing, this variance is most likely caused by variance made to the modulation as the system dynamically adjusts it to maintain the connection.

Additionally, the unique shape of the curve, with a peak in throughput at a distance of 4000 meters, is also unexpected. There are several reasons as to why the throughput at distances closer to the base station node than 4000 meters may have been less than those experienced at this distance. It is possible that environmental conditions, either spectral or physical, may have adversely affected transmissions at distances less than 4000 meters. Additional testing is necessary to determine if the unexpected shape of this curve is an anomaly or if this is the result of some unexpected system behavior either due to design, user error, or equipment fault.

Despite the unexpected occurrences, the Carlson Rural Connect was able to facilitate effective communication at over twice the distance possible utilizing the Harris 7800MP. Additionally, the throughput achieved utilizing the Rural Connect was also significantly greater than the throughput of the Harris 7800MP regardless of distance.

4.4 Multi-Hop Testing

Planned multi-hop testing was attempted, as detailed in Chapter 3, however all attempts to establish a viable connection between the emplaced Iperf server and client were unsuccessful. The client and server were placed at opposing ends of the constructed Rural Connect network and thus traffic from one node to the other was forced to take two hops to arrive at its destination. A viable connection did exist between each of the Rural Connect client radios and the Rural Connect base station. This connection was verified utilizing both the Rural Connect GUI, accessed via the base station node, and via Iperf client and server establishment from a client placed at the base station to the client at each Rural Connect client radio.

This line of experimentation necessitated the establishment of two client nodes. Iperf connections were possible from the base station to each of the clients, but it was not possible to produce a connection between an Iperf client on one of the Rural Connect client radios, across the Rural Connect base station to a server on the other Rural Connect client radio regardless of modulation settings or connection strength. In this case it was not possible to transmit Internet Control Message Protocol (ICMP) traffic between the clients.

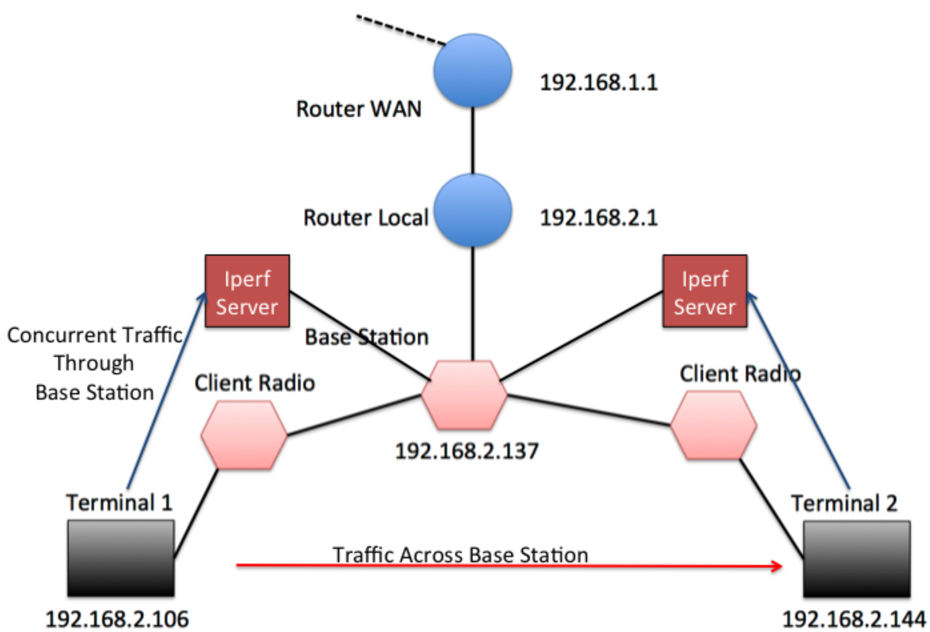
In order to rule out an IP addressing issue, a wired connection between all three radios, two clients and the base station, was utilized in order to attempt to rule out any transmis-

sion issues. An IP addressing issue was ruled out since ICMP traffic was able to be passed between the client systems connected to each Rural Connect client radio and an Iperf connection was able to be established between the two client systems. However the data rate, while utilizing a wired radio connection, was negligible.

4.4.1 Bandwidth Division Limitations

After discussing the issues experienced with the technical staff at Carlson Wireless, the issue causing the inability to connect across multiple hops was identified as a bandwidth division issue at the base station. As detailed in Chapter 3, the Carlson Rural Connect TV utilizes a weightless link layer protocol to handle communications internal to the system. The client radios themselves do not have an IP address. Instead these radios utilize a predefined addressing scheme that is utilized by the base station to direct traffic. This protocol does not afford any control or division of the bandwidth available to the base station. The egress of traffic from each client radio, and subsequent ingress into the base station radio, is not controlled in any manner. No division of time or frequency exists to ensure that congestion does not occur at the base station.

Figure 4.7: Depiction of bandwidth division issues: Carlson Rural Connect



Following the identification of this issue, additional experimentation was conducted in an attempt to determine the effects of this inability to control bandwidth usage at the base station. It stands to reason that if traffic crossing the base station from one client to another is affected by the base station's difficulty dividing bandwidth, then traffic passing through the base station to an individual requesting or transmitting clients would also be affected. Serving multiple clients from a single base station also requires the division of available bandwidth in order to avoid congestion, collisions, and lost data.

The scenario presented in Figure 4.7 was setup and data was sent both concurrently and by one Iperf client at a time in an effort to determine throughput rate changes in each scenario. As identified in the passive scanning experiment, the Rural Connect system sends data between the base station and client nodes to maintain the connection. Conducting throughput testing while this connection was being maintained, rather than actively transmitting data, presented an opportunity to identify bandwidth issues that this maintenance might cause. Finally, the same experiment was repeated utilizing a wired connection between each of the radios to ensure that the effect remained to some degree and to rule out any interference issues cause by multiple clients operating in the same relative location.

The results of these tests are presented in Table 4.4.

Table 4.4: Results of throughput analysis of Rural Connect network with multiple clients

Clients attached to network/ Clients transmitting data	Throughput (kb/s)	Standard Deviation
1/1	1918.386	753.509
2/1	143.719	346.132
2/2 (concurrent transmission)	751.266	1010.012
2/1 (wired radio links)	2987.273	2614.394

The decrease in throughput rate in cases where two nodes are attached to the network is evident. Additionally, the increase in standard deviation for all results reveals the large number of cases where transmissions failed and resulted in a throughput of 0 kb/s. The addition of more client nodes to the network, and subsequent addition of traffic through the base station, appears to have created congestion, as the traffic fights for available bandwidth through the base station.

Following analysis of the traffic resulting from this testing, it appears that the random access protocol utilized by the white space network is most probably the pure Aloha protocol. The Aloha protocol is an "un-slotted and fully decentralized protocol" that allows multiple clients to access a single network [24]. Use of the Aloha protocol results in a relationship between network performance and traffic offered the network by clients. After a certain point, dependent on the network type and configuration, an increase in offered load becomes detrimental to network performance. In the case of the Rural Connect, the traffic offered by the single transmitting client provides a load sufficient such that any additional traffic exceeds the networks ability to handle the offered load. In the case of this experimentation, the Iperf client was configured to place a constant load, in the form of TCP traffic, on the network. It is possible that multi-hop traffic may have been more successful utilizing a different Iperf configuration which might have produced less overall traffic on the network.

4.4.2 Simulation Results

The results gathered from real world experimentation provided a platform upon which a multi-hop network could be analyzed utilizing simulation. The simulation was created in NS-3 using the calculations specified in Chapter 3. Refinements were made to the simulation in order to ensure the performance more closely mirrored real world results. The model was modified to ensure the free space loss characteristics produced similar results to those experienced in the terrain and under the conditions experienced via tactical testing. One characteristic that was not reproducible was the throughput speed achieved at shorter ranges. Table 4.5 presents the speeds achieved at respective node distances. A comparison between these results and those presented in Table 4.3 reveal that at shorter distances, on average, the real world device produced faster throughput rates than the simulation. Given the design of the network, as detailed in Chapter 3, the total distance traveled by data is twice the node separation distance as the network is composed of two white space hops.

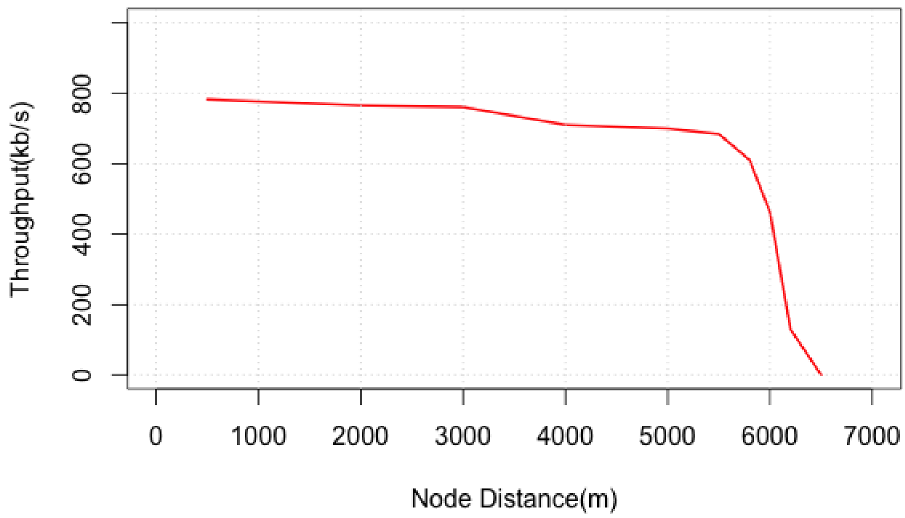
Table 4.5: Results of White Space simulation transmitting 2000 kb at varying node distances

Node Distance (meters)	Total Packet Travel Distance(meters)	Time to Complete Trans of 2000 kbs (secs)	Throughput (kb/s)
500	1000	2.556	782.468
1000	2000	2.576	776.434
2000	4000	2.614	765.151
3000	6000	2.63	760.592
4000	8000	2.817	709.956
5000	10000	2.859	699.446
5500	11000	2.923	684.113
5800	11600	3.276	610.423
6000	12000	4.325	462.438
6200	12400	15.422	129.682
6500	13000	not completed	0

The simulation does somewhat model the behavior of Rural Connect suite as the nodes reach the outer limits of the distance at which they are able to maintain a connection with the base station. As the node distance is increased the throughput begins to decrease and the time to complete the transmission grows significantly. From analysis of the generated packet captures, it is apparent that this is due to the loss of several packets and the necessitation of numerous retransmissions. Ultimately, throughput becomes negligible across the entire network.

The simulation provides insight into the potential use of Rural Connect suite as a means of expanding the effective range of communications rapidly. At shorter distances, real world testing shows that a higher throughput is to be expected, on average. In this case, the throughput through this multi-hop network might increase, assuming the bandwidth division shortcomings discussed were handled in order to take advantage of the higher single-hop throughput. At greater distances the simulation reveals that usable data rates are possible and a model for the decay of the network as distance increases is presented. This decay closely mirrors the behavior experienced in a single hop network while providing insight into the behavior of a network utilizing multiple white space network hops.

Figure 4.8: Graph of simulation results: TCP transmission of 2000 kb at varying node distances



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CHAPTER 5: Conclusions

White space technology has the potential to add value to military operations in terms of spectrum agility and the need for over-the-horizon communications. However, at this point, the technology is not ready or mature enough for deployment in support of military operations. It is likely, given a cooperative development effort by industry entities already involved in the development of this technology and government users, that this technology could be ready for military use in five years.

Given a concerted development effort, future iterations of this technology could have a significant impact on the means of handling spectrum management in military operations. Currently managing and deconflicting the limited spectral space available for units to utilize in order to establish tactical communications is a significant effort. A great deal of doctrine is dedicated to process and procedures that facilitate this process [25]. White Space technology presents the possibility of automating a significant amount of this effort at the tactical level, possibly echelons higher, by allowing the spectrum sensing and analyzing abilities of the radios in use to ensure adequate communications links and viable channels with limited input from users.

Additionally, White Space technology has the potential to be used as a platform to facilitate rapidly expanding networks capable of over-the-horizon communications. White Space devices utilize a frequency range capable of propagation through varying terrain and over long distances, as demonstrated through years of use delivering television signals. The means of base station and client communication also lends itself to the construction of a mesh infrastructure that, if developed, could change the way military communications infrastructures are planned and implemented.

5.1 Usability

The device tested, the Carlson Rural Connect, was not designed specifically for use in the environment in which it was tested. The system is designed for a planned and static emplacement designed to take maximum advantage of the waveform and adaptive frequency

properties of the system. Due to this fact, the system is lacking in many areas related to tactical usability when compared to the Harris 7800MP and other radio platforms designed for tactical use.

The Harris Radio is compact and easily deployed. The means of provisioning power to the system only minimally increases its footprint due to a design that includes compartmentalized storage for batteries which allows for the inclusion into vehicle mounted system. The batteries designed for use with the system provide power for several hours of operation and include chargers that are designed to be used in military vehicles. Though special antennas are available for use, the system is functional with simple antennas that are easily deployed and stored, allowing for ease of movement and rapid setup. Programming the radios is difficult in the field and primarily relies on pre-planning of operations to ensure that network connections are made between radios. Reprogramming on the move requires additional steps and is somewhat difficult to adapt to a changing environment, both in terms of frequency use and networked connections.

The Rural Connect is an example of the usability potential of the white space platform and provides insight into many of the advantages of this technology. Adaptation in terms of frequency use and network planning could potentially leave little for the user to deal with once deployed. Rather than a significant process to shape a network, adjust a designed network plan, or change an operating frequency, the Rural Connect displays the ability of white space technology to potentially allow these tasks to be performed without significant user intervention. This suite of radios is able to handle identification of the most usable frequency and adapt to environmental or jamming borne interference while still allowing the network to be shaped according to the emplacement of nodes. The majority of the coordinating tasks are handled by the system, or a centrally located control, while the user worries about a few inputs made via an easy to use graphical interface.

While there are usability advantages to this system, there are issues that are primarily a result of the designed purpose of the system. Unlike the Harris Radio implementation, the Rural Connect lacks design factors that maximize usability in the tactical environment. In order to be useful in this environment, this system requires a dedicated and focused development effort. Creating a more rugged platform suited to the elements encountered in austere conditions is necessary. Additionally, the system must be made more compact. The

increased systems and capabilities available in the modern battlefield require an increasing amount of space. Developing this platform so that its advantageous functionality remains while ensuring that its form factor fits with the space available for the execution of front-line operations, is essential. Given a concerted development effort, focused on the tailoring of this technology suite towards use in the tactical environment, there is no inherent limiting factors preventing it from being as useful as currently existing systems. Alternatively, this functionality could be developed for inclusion into communications solutions deployed throughout the military from developers such as Harris or Persistent Systems.

5.2 Performance

Research and analysis conducted to examine the performance characteristics of White Space technology in general and the Carlson implementation specifically, reveal that this technology holds a great deal of promise. Communications in the tactical environment, currently constrained by the limitations of available devices and the congestion of available spectral space, could benefit a great deal from a device that performs in a similar manner to the current implementations of White Space technology such as the Carlson Rural Connect TV.

5.2.1 Distance and Throughput

Throughout testing, the White Space radio displayed the ability to communicate far outside the range of the Harris 7800MP radio even while operating at similar frequencies. The White Space radio was able to produce usable throughput at over twice the distance of the Harris radio.

On average, the White Space system produced a higher throughput rate than the Harris radio. This increase in throughput was significant for the majority of iterations and distances at which tests were conducted. As evident in Figure 4.5, there were virtually no instances were the lowest throughput rate experienced on the Rural Connect suite did not exceed the throughput rate experienced on the Harris radio. This is significant as it displays the ability of this technology to effectively utilize a frequency range that is able to propagate through terrain and over large distances as well as to make requisite adaptations to the exact frequency and modulation utilized in order to produce significant data rate increases as compared to existing and deployed technology.

An issue discovered during testing regarding the throughput performance of the white space radio was the throughput fluctuation produced by the suite during the numerous testing iterations. As previously discussed, this fluctuation is most likely caused by changes to the modulation rate as the radio responds to the spectral environment and the connection strength. Development focused on stabilizing this fluctuation would seem to be beneficial to the system. Specifically, for use in military operations, a reliable speed is essential if data is to flow over this network in order to connect other systems at a significant range. If a network composed of white space hops is to be utilized for the transmission data meant to integrate other systems, then it is likely that such large fluctuation ranges must be stabilized. The availability of the top end performance range is beneficial to civilian deployments of White Space systems as discussed in Chapter 2, where conditions can be modified, tested and refined in order to achieve maximum benefits. Military operations often do not afford the ability to ideally refine the environmental conditions the radio will operate in. In this case, a more tolerant and stable system will allow other systems to take advantage of stable provisioned links to transmit essential data and afford predictability to the users of the system.

Overall, the promise of white space technology, in terms of propagation distance and throughput, is apparent. This technology has the ability to advance military capabilities and add to the arsenal of capable over-the-horizon communications systems. Before the potential of this system can be realized the design of the system must be refined with an emphasis on stabilizing performance and producing a system that operates with some level of predictability under less than ideal conditions.

5.2.2 Bandwidth and Network Limitations

Given the nature of military operations, the ability to rapidly construct and adjust a network is essential. A device being utilized as a communications relay in this environment must be flexible and capable of facilitating growth and a mesh, or mesh like, architecture. Essential to this functionality is the capability of a system to allow data to take multiple hops across nodes in order for the transmitted data to reliably arrive at its ultimate destination.

The Carlson Rural Connect does not currently support the ability for multi-hop architectures, as evidenced by the results of the numerous tests conducted to examine this capa-

bility. The bandwidth division limitations of the system are a result of design decisions made by the company developing the system. Developers at Carlson Wireless stated that this functionality is not currently on schedule for development and throughout the course of preliminary research, it appears that other entities developing similar technology do not currently support a multi-hop capability, choosing instead to support capabilities that are more relevant to current deployments of the system.

Additionally, the challenges partitioning bandwidth between multiple client nodes would pose a large problem for use in an environment where multiple entities may possibly be demanding constant service. This issue again presents a reliability issue that is intrinsic of military operations. Units relying on a relay for service need that service on-demand in a reliable manner. These units, or the systems they are using, may not be tolerant to poor connections due to the relay infrastructure's inability to split bandwidth between two requesting clients. Delays like those experienced throughout the course of this experimentation, if experienced in a real world scenario, may greatly hinder the systems or military units relying on connectivity provisioned by the White Space suite.

The requirement for this capability and its development to a standard for use in military operations provides additional evidence for the necessity of a concerted development effort undertaken by military and industry entities. A basic functionality, such as the ability to support multi-hop architectures, is important to dynamic military operations. The use of a communications relay without this ability is not practical for military operations.

5.3 Maturity of Technology

In general White Space technology is in the early stages of development. The benefits of this technology are apparent and many different entities, companies and groups have begun developing in this field in order to remedy problems very similar to those faced by the military, namely spectrum management and signal propagation. Though these problems may differ in scope, urgency, and base requirements, the lines of effort produced by these developers have resulted in several systems that show a great deal of potential for use in military operations, given the increasing data requirements necessitated by recently developed war-fighting systems and enablers.

What is lacking is refinement of the standard for the technology being developed, both

in the civilian and military sector. A standard for Wireless Regional Area Networks exists [26], however the immaturity of the technology has not yet allowed for the establishment of industry wide standards versus proprietary means of solving problems. More mature technologies, such as Wifi and its different variations rely on a more in-depth standard to dictate the operation of devices. [27] Currently, the existing standards for the operation of white space devices do not facilitate interoperability between the various proprietary solutions available. Instead there are many independent efforts, undertaken by several different companies and groups. The short term result of this uncoordinated development effort is equipment that is relatively expensive and difficult to obtain. The acquisition of equipment for the purpose of this study was difficult because of its limited availability and its lack of presence in any kind of military or government entity. Acquiring it took several months and an involved and difficult contracting process.

If this technology, and the benefits it provides, are going to be useful to the civilian and military sectors, a standard must be developed which details the basic operation of the devices, protocols used for their operation, and capabilities. Currently these devices operate in a very unique and proprietary manner, so any kind of interchangeable functionality is not possible and no standard services are provisioned. Instead of companies attempting to provision a defined service in a competitive manner, companies are producing a vision of their implementation of White Space technology to an undefined end. A standard set by the industry will aid in remedying this issue and make this technology more widely available and more beneficial to users.

Additionally, a cooperative development effort between the military and industry entities would be beneficial to produce a device that is capable of operating in environments unique to military operations. This research detailed the unique benefits of this technology and their relevance to military operations. However, several deficiencies due to non-military centric design efforts were also pointed out. The requirements of military use are unique and require a focused effort to accurately define and meet these needs.

5.4 Conclusions

White Space technology has the potential to enhance the communications capabilities of personnel operating in the tactical environment. This technology provides a means of en-

suring that spectrum space is utilized to its maximum potential in an environment where it might not be possible to deliberately plan its use. This could potentially facilitate the utilization of a seemingly small set of available frequencies by multiple units while not interfering with resident broadcast and utilization of adjacent frequencies.

White Space technology also makes use of wave forms and frequency ranges which have proven performance in austere and distant environments. The widespread use of broadcast television and its ability to reach users over a great distance from a broadcast location is evidence that this technology is capable of facilitating over-the-horizon communications.

Though great potential exists, a significant development effort is required if this technology is to achieve the reliability and performance necessary of systems utilized by military organizations. Given time for this technology to mature and refinement to the frequency sensing, adaptive, and network forming properties of the various implementations of white space technology, it is likely that the military will benefit from the inclusion of this technology into the communications systems fielded in the future.

5.5 Recommendations for Future Work

Though the simulation effort performed for this thesis provides some insight into the performance of a white space suite over multiple hops, a real world experiment is ideal for gathering data. Additional experimentation should be conducted to determine if different testing configurations might produce more favorable results. Configuring the testing platform to utilize UDP traffic and conducting an incremented increase off the offered load on the network might serve to reveal additional data about the networks performance. Ideally, this incremental increase would provide an understanding of the networks true capability to handle an offered load from one or multiple clients. A determination of the ability to handle load may allow for the testing of a multi-hop capability by limiting the offered load from each client attempting to get traffic across the base station node.

The experimentation for this thesis was executed utilizing a limited amount of equipment. Additional Rural Connect equipment, with an emphasis on base station devices, may have allowed for several more experiments to be executed and increased functionality. Utilizing a larger suite of equipment, additional multi-hop testing should be conducted in an attempt to gather additional data regarding performance. Given access to multiple base station and

client units it may be possible to create a node consisting of a hardwired base station and client, each belonging to a separate white space network, and a shared buffer. The client and base station node could each write to and read from the shared buffer creating a means to get information from one white space network to another. The construction of this special node introduces additional variables into the performance of the network, to include buffer read and write times, but may produce interesting data regarding multi-hop performance.

Following future development to existing white space communications suites, several lines of examination should take place in order to evaluate the preparedness of this technology for deployment in military operations. The limitations of current implementations prevented the testing of a large network formed utilizing White Space technology base and client nodes as a backbone. The examination of a network of this type is vital in determining the usefulness of this technology in the military. Following an examination of this type this technology, in the form of suites from various vendors, should be tested in a large scale communications exercise such as a Network Integration Exercise.

List of References

[1] N. Albert, "Taking advantage of opportunities for commercial satellite communications services," Defense Business Board, pp. 1–11, Feb. 2013.

[2] *Operations*, FM 3-0, Headquarters: Department of the Army, 2008, 6.1-6.5.

[3] *Tactical Radio Operations*, FM 6-02.53, Headquarters: Department of the Army, 2009, 4.1 - 4.22.

[4] H. Corp, *U.S. Army Brigade Combat Teams to Validate Communications Backbone Architecture Using Harris Falcon II Wideband Radio Systems During Network Integration Evaluation 12.2*, 2012. [Online]. Available: http://rf.harris.com/news/view_pressrelease.asp?act=lookup&pr_id=3455

[5] "Mobile ad hoc network with dynamic tdma slot assignments and related methods," U.S. Patent 5 668 842, Apr. 25, 2013.

[6] J. Dollard, A. Garcia, M. Johnson, W. Llivichuzhaca, and M. Vanwinkle, "Evaluating dynamic spectrum access on the wireless network after next radio," M.S. Thesis, Telecommunications Systems Engineering Course, Fort Gordon, GA, 2014.

[7] P. Systems, *Technology*, 2012. [Online]. Available: http://www.persistentsystems.com/persistent-systems-technology-intro/

[8] P. Systems, *Quad Radio Router*, 2014. [Online]. Available: http://www.persistentsystems.com/pdf/Quad_SpecSheet.pdf

[9] J. Neuhaus. (2005). Cable TV channel frequencies. [Online]. Available: http://www.jneuhaus.com/fccindex/cablech.html

[10] F. C. Commission. (2007). Digital television. [Online]. Available: http://www.fcc.gov/digital-television

[11] F. C. Commission. (2008). Auction 73 - 700 mhz band. [Online]. Available: http://wireless.fcc.gov/auctions/default.htm?job=auction_factsheet&id=73

[12] C. for White Space Communications University of Strathclyde. (2008). What is white space? [Online]. Available: wirelesswhitespace.org

[13] E. Bangeman. (2007). The white space coalition's plans for fast wireless broadband. [Online]. Available: http://arstechnica.com/gadgets/2007/04/white-space

[14] M. Lasar. (2009). Broadcasters sue fcc over white space broadband decision. [Online]. Available: http://arstechnica.com/tech-policy/2009/03/broadcasters-sue-fcc-over-white-space-broadband-decision

[15] Federal Communications Commission, "Unlicensed operation in the TV broadcast bands," Washington, D.C., Apr. 2012.

[16] M. Research. (2015). Pilots and demonstrations. [Online]. Available: http://research.microsoft.com/en-us/projects/spectrum/pilots.aspx

[17] J. Bolt, "Nation's first campus 'Super WiFi' network launches at West Virginia University," *WVU Today*, Nov. 2015.

[18] M. Waddel, S. Thilakwardana, and T. Harold, "Performance of an experimental white space base station for mobile and fixed broadband applications," British Broadcasting Corporation, May 2012.

[19] C. W. Technologies. (2014). Ruralconnect spec sheet - throughput/modulation selection examples. [Online]. Available: http://www.carlsonwireless.com/rural-connect-spec-sheet/

[20] P. Bahl, R. Chandra, T. Moscibroda, R. Murty, and M. Welsh, "White space networking with wi-fi like connectivity," Microsoft Research/Harvard University, Aug. 2009.

[21] *RuralConnect: Modulation Selections*, modulation overview, Carlson Wireless Technologies Inc., 2014.

[22] M. Stoffers and G. Riley, "Comparing the ns-3 propagation models," White Paper, Georgia Institute of Technology, Mar. 2014.

[23] S. Sanchez, "Modeling a multi-hop architecture using white space devices," Naval Postgraduate School, Monterey, CA, Tech. Rep., feb 2015.

[24] J. Kurose and K. Ross, *Computer Networking: A Top Down Approach*. Boston, MA: Pearson Education Inc, 2013, p. 452.

[25] *Joint Electromagnetic Spectrum Management Operations*, JP 6-01, DC: U.S. Joint Chiefs of Staff, 2012, I.1 - VI.5.

[26] A. N. Mody and G. Chouinard, *IEEE standard for information technology–telecommunications and information exchange between systems–wireless regional area networks (WRAN)–specific requirements. policies and procedures for operation in the TV bands*. New York: Institute of Electrical and Electronics Engineers, 2011.

[27] P. Calhoun, C. S. Inc, M. Montemurro, D. Stanley, R. I. Motion, and A. Networks, "Control and provisioning of wireless access points protocol binding for ieee 802.11," 5 2009, RFC 5416.

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